The Space Interferometry Mission:

Taking the Measure of the Universe

Final Report
of the
Space Interferometry Science Working Group

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Executive Summary

In 1991 the National Research Council commissioned the Astronomy and Astrophysics Survey Committee, chaired by John Bahcall, to recommend new ground- and space-based programs for the 1990's. That committee urged only one major new space start, the Astrometric Interferometry Mission.

Responding, NASA's Office of Space Science, Astrophysics Division convened the Space Interferometry Science Working Group. During its four plus years of existence the Working Group was asked for advice on three major issues: the best AIM architecture, long term space interferometry strategy, and the role of AIM as a technology precursor for later interferometry missions. In the expanded role of astrometric instrument and technology precursor, AIM was rechristened SIM, the Space Interferometry Mission.

In dealing with these issues the Working Group came to understand the tremendous breadth and depth of the contributions that SIM could make, both in advancing Astronomy and Astrophysics, and in setting the stage for even more sophisticated space instrumentation. In this report we outline the astronomical and astrophysical issues that will be impacted by SIM. The precision of the positions, parallaxes and proper motions will affect everything from measuring Earth crustal dynamics to gauging the age of the Universe. The mission will demonstrate aperture synthesis imaging and deep central nulling – required for future planetary search missions.

Further, SIM will demonstrate technologies that are critical to future missions, including metrology and control in the picometer range, vibration suppression and control at those levels, and large scale space deployment of precision structures.

In what follows, the final report of the Working Group, we summarize what we have learned about the capabilities of this proposed mission, the state of its development and the role it will play in preparing the way for future space missions. We have concluded that SIM is a step in developing space instrumentation that cannot be skipped, and an opportunity for Astronomy that must not be missed. We hope that when finished, the reader will share that enthusiasm with the members of the Working Group.

Contents

1 Introduction

As a technique for enhancing spatial resolution in astronomical images, interferometry has its origins in the pioneering work of Fizeau (1868) and Michelson (1891). Michelson's early measurement of the diameters of Jupiter's Galilean moons showed the promise of the technique. However, while many important and fundamental measurements have been made since (for a recent review see the article by Armstrong, Hutter, Johnston and Mozurkewich in *Physics Today,* May 1995, 42), the contributions of the technique have been episodic. It has had relatively limited impact on the field generally.

In contrast, at almost the same time photography was introduced to astronomy and the effect was immediate and dramatic. Astrometry, the art of measuring precise positions and their time variations, which had essentially defined what was observational astronomy over the centuries, experienced a renaissance with the ability of plates to record wide fields to much fainter limiting magnitudes. All-sky cataloging projects, proper motion surveys, long term parallax campaigns, and proper motion membership studies of nearby clusters, name but a few of the major advances enabled by the new detector.

Ironically, the advent of photographic plates also lead to the long term decline and near demise of astrometry as an active branch of astronomy. On the one hand, the data reduction and archiving problems encountered with the large photographic projects were nearly beyond the technology of the era. Further, the deleterious effects of the atmosphere quickly became the major limitation to the newly designed wide field or long focus telescopes being used with the plates. So even as it became clear that we lived in a much larger and more complex universe than we had imagined, we ran out of the ability to take its measure.

On the other hand, it was now possible to record objects with surface brightnesses well beyond the capabilities of visual observers. And more, one could contemplate dispersing the light from faint celestial sources, recording it as a detectable signal. The introduction of photographic plates opened the door for modern astrophysics.

For all those limitations, and add the extreme competition that developed for telescope time, the products of the age-old practice of astrometry were too valuable for the field to simply die. Astrophysicists found that they were constantly being stymied by the lack of knowledge the kinematics of stellar systems, for example. One of the most powerful tools available to astronomers in understanding the nature of new and exotic objects are arguments based on the conservation of energy. Since inferred luminosities depend on square of distance, the lack of good parallaxes to even fairly nearby objects was keenly felt. On the largest scales, the evaluation of the Hubble constant, and in turn the age of the universe, was seriously undermined by the many layers of the bootstrap process used in place of direct distance measurements.

In the meantime, major advances have been taken in the practice of astronomical interferometry, ground based and (potentially) space based. They are driven by the dramatic breakthroughs in modern electronics. Ground based arrays are nearing completion that will allow imaging over limited but finite fields at resolutions exceeding a milliarcsecond (mas) and detection of motions of stellar objects down to 10 microarcseconds (μas), levels that were unimaginable only a decade ago.

These extraordinary advances notwithstanding, neutralizing the effects of the atmosphere for two critical kinds of measurements appears to be beyond foreseeable capabilities. For the purposes of very high dynamic range ($\geq 10^6$) imaging at mas resolution, or very high precision, absolute parallaxes ($\sim$ μas) and proper motions ($\sim$ μas yr^{-1}), the interferometers must be space based.

This is hardly to be viewed as a drawback. The above characteristics describe instruments that in single strokes will push back existing barriers by orders of magnitude. High dynamic range imaging in the mid-infrared will enable direct imaging of nearby planetary systems. The astrometric instrument will improve on the current parallaxes by a factor of a thousand and on the best proper motions by a factor of a hundred.

In this report we describe the efforts of the Space Interferometry Science Working Group (SISWG) to characterize the science that would be enabled, implementing such an unprecedented improvement in astrometric capability and the various steps and deliberations taken to provide NASA Astrophysics with advice on how to proceed in the development of such an experiment. In the process we were also asked to help identify the logical development path toward a future mission aimed at planetary detection and characterization, and describe the committee's conclusions on that issue as well.

What follows is, we believe, a rather unusual document, created out of unusual circumstances. After a brief description of the nature of the committee and the history of its deliberations, we try to provide some flavor of the breadth of the impact that the Space Interferometry Mission (SIM) will make on Astronomy. We do this not first by outlining the mission's potential contributions, and then by going into some depth on what may be accomplished with a handful of current, real astronomical problems. The possibilities in every case are impressive and give more than a glimpse at the potential of this experiment.

Astrometry is alive and well in other countries as well, and we make specific note of the interest being taken by the European community in this general area and of their proposed GAIA satellite. Rather than being competitive, we show that the proposed instruments are so different in concept that it is their complementarity that is notable.

Finally, the report provides an expanded summary of a technical evaluation of the Orbiting Stellar Interferometer (OSI) design proposed as the SIM instrument and the suggested augmentations that would allow it to act as a precursor to the planetary search instrument. Although the full technical evaluation is available separately, the summary is included to provide some flavor of the remarkable technology advances that have been made, or are in the offing, that make this instrument a real possibility.

We hope that by providing this report we will give the community some sense of the truly unique capabilities endowed in this instrument, and the potential contributions it will make toward understanding our Universe.

2 History of Working Group: Documents and Recommendations Already Produced

The SISWG was constituted in late 1991 by NASA's Astrophysics Division (Code SZ) in response to the strong endorsement given in the National Research Council decadel recommendations, the "Bahcall Report", to the Astrometric Interferometry Mission (AIM). The broad goals of AIM, as described in the Bahcall Report (eg. p.85), are to achieve wide-angle astrometry on 20th magnitude stellar objects to a precision of 30 μas or better. The search for extra solar planets figured prominently in the scientific justification, and mission lifetimes of the order of 5 years or more were implied.

The committee, chaired by Steve Ridgway (NOAO), was charged with the task of deciding which if either of two proposed instruments, the Orbiting Stellar Interferometer (OSI; a JPL effort lead by Mike Shao) or the Precision Optical INTerferometer in Space (POINTS; a Center for Astrophysics effort lead by Robert Reasenberg and originally conceived by Irwin Shapiro), should be selected for development (the "downselect"). In addition, the committee was asked to make recommendations on long term strategy for the development of space interferometry for Astrophysics.

The committee started at its tasks on two fronts. First, in order to establish a metric against which to compare the two instruments a Strawman Science Proposal was drafted. This document, later revised (see below), was designed to sample a small number of realistic, important astronomical problems in enough detail that the two teams could make specific statements as to their instruments capabilities toward the measurements, including required integration times. While specific problems were identified in the Strawman, the goal was not to provide a comprehensive first guess of the program of an AIM instrument, nor to lay claims to specific pieces of science, but to sample the observing parameter space that would be required of the instrument.

Secondly, on-site visits by the SISWG were scheduled at the JPL and CfA laboratories in order to assess the state of the technology developments of the two groups and the level of commitments of the two institutions. These latter visits were accomplished in 1992 (JPL) and 1993 (CfA). Late 1993 saw final drafting of the Strawman Science Proposal.

In the process of the various committee discussions, unofficial consensus was reached on several points. First, it was clear that the scientific case for an AIM was demanding. Second, the two instruments seemed to distinguish themselves on two levels. In terms of the criteria spelled out in the Bahcall Report, reaching 20th magnitude objects in reasonable integration times seemed possible for OSI and problematic for POINTS. On the other hand, while neither appeared to fit within the $250M cost cap of the Report, POINTS clearly had a better chance of achieving that limit.

The other distinguishing features of the two experiments were simplicity of design versus long-term ground based experience. These in particular were technical issues, ulitmately to be weighed by the technology panel.

Through most of the committee's tenure, imaging capabilities were disregarded, the Bahcall Report giving such emphasis to astrometry. This changed substantially in the latter months, given the growing role of the experiment as a technology precursor, as described below.

Finally, it was agreed that while the SISWG was very enthusiastic about the AIM science, it was felt not appropriate that the committee act as advocate for the experiment, and that some provision for advocacy was a critical need.

Early there was substantial frustration over the lack of coordination between the SISWG and the various groups considering interferometers with similiar pointing requirements to be used to search for extrasolar planets. Fortunately, this was dramatically reversed in the last couple months of the committee's existence (see below).

At the end of 1993 Ridgway asked to be excused from the Chair's responsibilities (while remaining a SISWG member) leading to the appointment of Deane Peterson (SUNY Stony Brook) as the new Chair. At this time Jeremy Mould, co-chair of the Science subpanel also resigned to be replaced by Robert Wilson (AT&T, now CfA). Robert Laskin (JPL) was appointed co-chair of the Technology subpanel at about this time as well.

In January 1994 the reconstituted SISWG, meeting for their third Plenary session, agreed to revisit the Science Strawman, since substantial time had passed, and to solicit the responses from the two instrument teams to the Strawman as it stood at that point. Although it was expected that these would be the penultimate steps taken before instituting the formal downselect, late in the summer of 1994 the SISWG was informed by Code SZ that the selection process was being put on hold. Two rationales were provided. First, it was clear that future funding for major missions was being severely constrained; it was no longer realistic to expect a "new start" status for an AIM mission before the turn of the millennium, a timescale implicit in the Bahcall report.

Secondly, from preliminary estimates neither of the proposed instruments would easily fit within the $250 Million (1990) cost cap recommended in that report. Code SZ felt that given the delay and projected costs, AIM needed reevaluation by the Astronomical community. The SISWG was asked to redirect their efforts to the other half of the original charge and to recommend a long term strategy on space interferometry.

In the meantime, Code SZ had solicited proposals for the Future Missions Concepts program. Interferometry fared well in the February 1995 reviews with OSI the top rated proposal from the Optical - UV panel and POINTS not far behind. Simultaneously, Code SL, the Planetary Science Division, was embarking on an agressive effort to define a roadmap that would lead to detection of Earthlike planets around nearby stars. These events caused a reevaluation of the viability of AIM by Code SZ and the SISWG was asked to consider whether OSI could provide AIM science, and to participate in the Code SL roadmap process to see how AIM could be integrated with that effort.

By late summer of 1995 it was clear that a significant role could be taken by OSI in the ExNPS (Exploration of Neighboring Planetary Systems) process, and Code SZ formalized the changes in the SISWG charge. The committee was asked to determine whether there was an instrument that could provide the AIM science and that could act as a technology precursor for the interferometers being proposed for the planet search. The committee was asked to respond to these questions by October 1. Although the charge did not exclude POINTS from consideration, the committee made clear to Code SZ that there was not sufficient time to bring the POINTS proposal back fully into the review process and meet the deadline imposed. Code SZ agreed that the committee could limit consideration to whether the OSI proposal would satisfy the requirements set forth in the revised charge.

On September 30, 1995 the SISWG submitted to Code SZ a document certifying that the OSI design, in it's nominal 7 meter baseline design, could meet AIM science goals. Further, the committee certified that the experiment could act as a major technology precursor for the ExNPS interferometer, particularly if an extension of the truss to 20 meters, with deployment in space as a significant aspect of the extension, were added. (With this dual role the Astrometric Interferometry Mission has been rechristened the Space Interferometry Mission, SIM). The certification by the SISWG is available as a separate document, but an extensive summary of the conclusions, reached primarily by the Technology panel, is included here as Section 8.

Consistent with the Headquarters-wide reorganization in NASA, the SISWG will stand down with the completion of this final report, early in 1996.

3 The Science Enabled by the Space Interferometry Mission

The proposed capabilities of SIM are simply stated: about a thousand times better in position, parallax, and proper motion accuracy than currently available, and to limiting magnitudes approaching 20. This is a sufficiently large jump that it is not so easily comprehended. Distances accurate to 10 percent currently are limited to 50 pc, possibly to be increased to 100 pc by Hipparcos. SIM will increase this sphere's volume by 10^9. Correspondingly enormous improvements in proper motions and transverse velocities will be possible. Not unexpectedly, these capabilities will affect much of Astronomy.

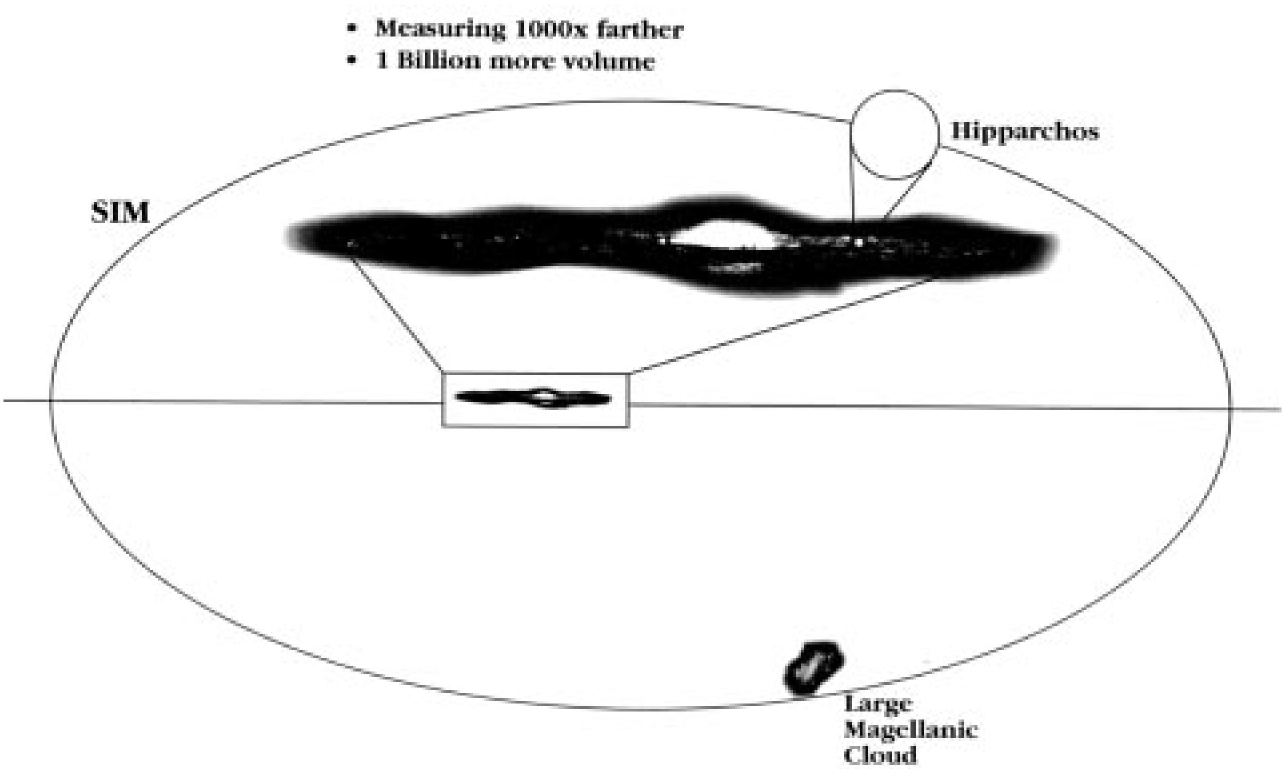

Figure 1: With the thousandfold increase in parallax capabilities, accurate distances to any object brighter than 20th magnitude within the Galaxy *and* the Magellanic Clouds will be possible.

In order to assess the impact of the SIM on various astrophysical problems, we consider its effect on the three areas of astrometric measurement: positions, parallaxes, and proper motions, and examine various astronomical areas and problems in light of the expected accuracies. We consider the science enabled by two levels of accuracy, the 5 microarcsecond accuracy of the baseline SIM and the 1 microarcsecond accuracy of an enhanced (truss extended to 20 m) SIM. The difference in complexity, risk, and cost between the baseline and enhanced SIMs will not be considered here. Beyond astrometry, SIM will also demonstrate interferometric imaging techniques in space and the peculiar capability of deep on-axis nulling. The implications of these capabilities will be discussed in later sections.

As a point of departure, Table 1 gives typical and approximate values for astrometric observables for a variety of astronomical objects, generally by type of object, and generally with increasing distance. The first column is the type of object (or a specific example). The second column gives the distance and the parallax underneath. The third column gives a “global” or ”systemic” motion in $\mathrm{km\,s^{-1}}$ and in angular units as would be seen from the Earth of the object or objects with respect to a larger entity, such as the motion of stars with respect to the galaxy, or with respect to the local standard of rest defined by the local group of galaxies, for example. The fourth column gives the “internal” or ”peculiar” motions again in both $\mathrm{km\,s^{-1}}$ and in angular units as seen from the earth, for example for stars moving within a spiral arm. The fifth column gives the equivalent absolute magnitudes for objects with apparent magnitudes 15 and 20 at the distance in column 2. Any target with absolute magnitude at those limits could be observed easily (*i.e.*15th magnitude in fifteen minutes, see section 8) or barely (20th magnitude in tens of hours) with the baselined SIM, at the indicated distance (the effects of reddening have been ignored). We refer to these two fiducial magnitudes below as the ”short” and ”long” exposure cases.

3.1 General Relativity

The fabric of the universe is described by different theories of gravity. The basic theory which underlies our current concepts of space, time, matter, and energy, is Einstein’s General Theory of Relativity (GR). Other theories which are extensions or alternatives to GR show deviations from GR at levels which are at or below the accuracies of current measurements. The accuracies of the proposed SIM will allow various measurement to be made which will test GR against these other theories to an extent never before possible. The relativistic parameter γ would be determined to one to two orders of magnitude higher accuracy than is presently possible. Such an accuracy would make a definitive distinction between GR and some alternative proposals.

With the level of accuracy of SIM, the quadrupole moment of the solar interior, generated by a high angular velocity in the interior, might be detectable. Frame dragging from the rotation of the sun and planets would be detectable. The size of the effects of MACHOs passing in front of stars would allow a determination of the mass of the MACHOs, just at the 1 μas level, (c.f. Miyamoto and Yoshii, Astron.J.,110, 1427 August 1995).

The second order effect of velocity aberration was needed to properly reduce the Hipparcos data at the one milliarcsecond level of accuracy. With SIM, the increased pointing accuracy will necessitate the use of the fully rigorous formulation of the velocity aberration and very accurate knowledge of the spacecraft’s velocity. In turn the knowledge of the velocity of the spacecraft will engender a severe test of aspects of both the special (the aberration) and general (time keeping on the spacecraft) theories of relativity.

Table 1: Astrometric Observables for Selected Astronomical Objects

Objects	Distance Parallax	Systemic	Peculiar Velocities ($\mathrm{km\,s^{-1}}$) Proper Motions ($\mathrm{yr^{-1}}$)	M_V reached at $m_V = 15, 20$
GALACTIC OBJECTS				
Nearest Stars	10 pc 100 mas	200 4″	20 400 mas	15, 20
Stars in Nearby Spiral Arms	2 kpc 500 μas	200 20 mas	5 500 μas	3.5, 8.5
Intermediate Dist. & Galactic Center	8 kpc 125 μas	200 5 mas	5 125 μas	0.5, 5.5
Objects at Edge of Milky Way	30 kpc 30 μas	400 2 mas	10 50 μas	-2.4, 2.6
Nearest Open Clusters	100 pc 10 mas	100 200 mas	5 10 mas	10, 15
Distance Across Hyades Cluster	40–50 pc 25–20 mas	35 160 mas	5 25 mas	11.8, 16.8
Typical Open Clusters	2 kpc 500 μas	200 20 mas	5 500 μas	3.5, 8.5
Interstellar Clouds Star Forming Regions	5 kpc 200 μas	100 4 mas	1 40 μas	1.5, 6.5
Typical Globular Clusters	10 kpc 100 μas	200 4 mas	2 40 μas	0.0, 5.0
EXTRAGALACTIC OBJECTS				
Magellanic Clouds	50–60 kpc 20 μas	200 800 μas	5–20 100 μas	-3.5, 1.5
Draco Dwarf Elliptical	80 kpc 12 μas	200 500 μas	10–100 25–250 μas	-4.5, 0.5
M31 Andromeda	700 kpc 1.4 μas	500 150 μas	10, 200 3, 60 μas	-9.5, -4.5
“Nearby” Active Galactic Nucleus	10 Mpc 0.1 μas	600 13 μas	3000 60 μas	-15.0, -10.0
Virgo Cluster of Galaxies	16 Mpc 0.06 μas	1200 15 μas	300 4 μas	-16.0, -11.0

3.2 Reference Frames

An "inertial" reference frame is defined dynamically within the context of General Relativity as one that has no external forces (real or apparent) acting on bodies observed within that frame. Such a coordinate system must be non-rotating by its nature; otherwise, each particle in that frame will "feel" an artificial acceleration due solely to the rotation of the frame itself. An extragalactic reference frame is assumed to approximate an inertial reference frame through Mach's Principle, and through the distance to the galaxies and quasars, making their transverse motions insensible to proper motion measurement.

Alternatively, a fundamental measurement of an inertial reference frame may be made through the minor planets. SIM observations of minor planets at the few microarcsecond level of accuracy would allow a truly inertial reference frame to be defined dynamically, without recourse to assumptions about the nature and apparent motions of extragalactic objects. The definition of such a reference frame is required if the observed motions at the $\mu\mathrm{as\,yr}^{-1}$ level are to be meaningful for kinematic and dynamic studies of galactic structure and motions and evolution, for example. Defining such a reference frame from the Hipparcos satellite was difficult because the observations of minor planets were made only when the scanning process took the aperture over an observable minor planet, which happened infrequently and at random. Therefore, the Hipparcos reference frame will be defined by the VLBI frame, rather than an independently defined and derived inertial frame. SIM will have the capability to observe a selected set of minor planets, and at times and positions which will optimize the determination of the inertial reference frame.

SIM will determine relationships among reference frames, including Optical, Dynamical, Radio, Extragalactic, and Infrared, for example. In particular, SIM will provide the basis for an independent reference frame at the highest available level of accuracy against which to measure the positions and motions of the celestial objects described below. This reference may be made truly inertial by the measurement of the positions and motions of solar system bodies directly. Then, by comparing the dynamical and extragalactic positions as a function of time, the first fundamental test of Mach's Principle will be possible at the microarcsecond level.

The relationship among other reference frames, particularly at different wavelengths, is extremely important because the "registration" of images and hence physical processes, observed at different wavelengths, is critical to our understanding of those processes in all types of objects from stars with material around them, to young stellar objects, to star-forming regions, to supernovae, to supernovae remnants, to galaxies, and to clusters of galaxies.

3.3 Planetary Searches

SIM is being considered in this document primarily for its astrophysical applications. In the meantime, NASA is undertaking a major effort outside the SIM to search for planets in neighboring stellar systems. However, because one of the scientific goals given in the Bahcall report was to "permit definitive searches for planets around stars as far away as 500 light-years through the wobbles of the parent star...", we consider briefly the role SIM may

TABLE 2: Stellar Orbit Size Due to Planetary Orbital Motion

Distance to Star (pc)	Star Mass (solar masses)	Planet Mass	Planet Orbit (AU)	Star Orbit (AU)	Orbit as seen on the sky Angular Diam.
1	1	0.001	5	0.005	5 mas
10	(G2V)	(Jupiter)			500 μas
100	(M_V=4.8)				50 μas
1000					5 μas
1	0.3	3×10^{-6}	1	3×10^{-6}	3 μas
3	(M5V)		1	3×10^{-6}	1 μas
	(M_V=11.8)				

With 5 μas accuracy, we could detect a Jupiter sized planet at Jupiter's distance from the Sun around a solar-type star out to 300 pc at the 3σ level of accuracy. With 1 μas accuracy we could detect an Earth sized planet at the Earth's distance fom the Sun around a red dwarf star out to 3 pc at the 3σ level of accuracy.

play scientifically in the search for neighboring planetary systems.

The view of the "Exploration of Neighboring Planetary Systems" (ExNPS) Integration Team (July 1995) was that SIM would play two roles in the "Road Map" toward achieving the goal of imaging an earth-like planet in a nearby planetary system. First, SIM will provide key technological demonstrations in situ, which will be *required* for a later interferometer with the capability of imaging (one pixel detection) an earth-sized planet. The technical capabilities include deploying precision structures, precision metrology, and extreme vibration damping. One particular demonstration, nulling a point source by a factor of 10^6, will be discussed in Section 5.

Second, and of direct relevance here, SIM would be capable of measuring the reflex motion of Jupiter-sized planets out to 150 pc (500 light-years), thereby extending groundbased searches. In fact this measurement can be made with substantial accuracy. The reflex motion of the Sun due to Jupiter's motion as seen at 150 pc could be detected to better than 10% and wobbles of Uranian mass planets (in 20 AU orbits) could be detected at 1-2σ (some typical examples are worked out in Table 3.3). However, characterization of orbits with periods in excess of ten years would be limited by the nominal mission lifetime.

A related example involves the recently discovered "planet" orbiting 51 Peg (Mayor and Queloz (1995) Nature, 378, 355). The minimum mass object (a half Jupiter mass in a 0.05 AU orbit) would produce a 3 μas wobble. This could be clearly seen by the extended baseline mission and the 7 m baseline mission would set a 3σ upper limit of 2.5 Jupiter masses, or provide an orbit for a larger object. The other two planetary mass objects recently reported orbiting 70 Vir and 47 UMa (Marcy and Butler (1996) ApJ Letters, in press, Butler and

Marcy (1996) ApJ Letters, in press) would produce reflex motions easily measured with the 7 m version, allowing determination of inclinations and acutal masses.

3.4 Stellar Studies

For the following considerations, an astrometric accuracy of 5 μas (rms) is assumed.

3.4.1 Stellar Evolution

The SIM instrument will allow the measurement of luminosities of objects throughout the HR diagram. From Table 1, all stars within 20 parsecs of the sun will have their distances and hence their luminosities calibrated to 1% or better. Motions of the nearby stars will be measurable to a fraction of a percent.

Out to the nearest spiral arms, 2 kpc, the distances and luminosities will also be calibrated to 1%, motions will be measured to 1% or better, but the "short exposure" stars will be limited to dwarfs with spectral type earlier than F5, while dwarfs between M0 and F5 will require significantly longer integrations. All giants and supergiants to 2 kpc are amenable to 1% distance determinations.

Out to the galactic center (or, equivalently a radius of 8 kpc from the sun, noting that no account is take of reddening), dwarfs earlier than A0 and giants later than K0 will be observable with "short exposure", dwarfs earlier than K0 and all giants and supergiants will be observable with the longer integrations. Parallaxes will be measurable to 4%, global motions to 1%, internal motions to 4%.

Out to the edge of the optical Milky Way (30 kpc), only supergiants will be observable with short exposures, while dwarfs earlier than F0 and all giants and supergiants will be observable with longer integrations. Distances and internal motions will be measurable to 20%, while global motions will be measurable to 1%.

For the nearest open clusters, we will be able to get a complete map of the cluster in 6-dimensional phase space (positions and motions in physical units within the cluster, assuming appropriate radial velocity data are available). For clusters out to 2 kpc, distances, internal and external motions will be observable at the 1% level. Stars will be limited to dwarfs earlier than F5 for short exposures. Dwarfs earlier than M0 will require longer integrations.

For typical interstellar clouds and star forming regions, at 5 kpc, stars will be limited to all giants and supergiants, and dwarfs earlier than A5 for short integrations, and dwarfs earlier than K5 for longer integrations. Parallaxes and global motions will be good to a few percent, but internal motions are expected to be smaller than in fully developed clusters, so the internal motions may be only good to 10%.

For typical globular clusters at 10 kpc, horizontal branch stars, and giants later than K0 will be measurable with short exposures, while earlier giants and dwarfs earlier than G5 will be amenable to longer exposures. The parallaxes will be good to 5%, the global motions to 1%, and the internal motions to 15%.

Given these observational constraints, some typical problems in stellar astronomy that will be amenable to solution, or at least observational definition include:

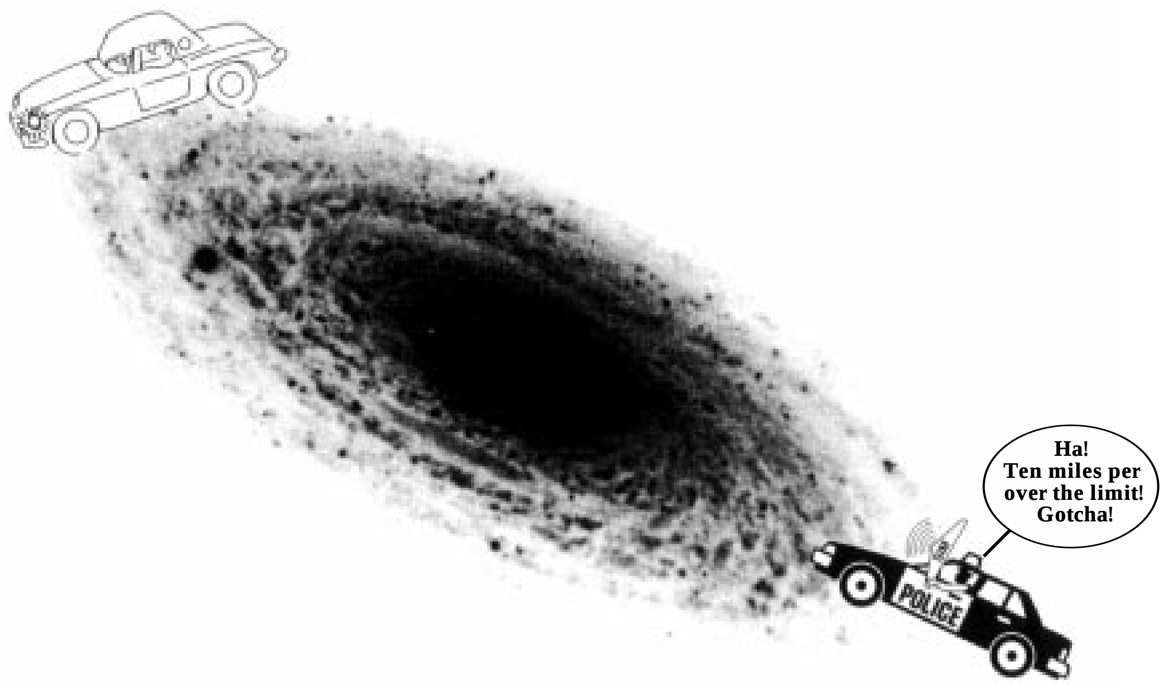

Figure 2: With μas positions and a five year mission, proper motions accurate to a few tenths of a $\mu\mathrm{as\,yr}^{-1}$ are possible. A half $\mu\mathrm{as\,yr}^{-1}$ corresponds to a velocity of only $5\,\mathrm{m\,s}^{-1}$ (10 mph, English units) at 2 kpc.

1. Observational definition the evolutionary states of stars with specific radii, masses, chemical compositions, and ages.

2. Redefinition of the standard isochrones for stellar evolution models.

3. Determination of the dynamics and stellar evolution in multiple star systems where mass exchange is significant using the distances and orbits of multiple star systems.

4. Determination of white dwarf masses, black hole candidate masses, hierarchical triples and binary kinematics, and kinematics and dynamics of Be stars and x-ray binaries.

For specific objects, distances or luminosities and motions could be determined for:

- WR stars
- η Carina
- Cyg X-1
- SS 433
- young stars above the galactic plane
- runaway stars

- RS CVn
- dMe stars
- stars with winds
- late type maser emitters

Questions that could be answered include where these fit into the scheme of general object formation and evolution.

3.4.2 Galactic Constituent Studies

For systems of stars and other massive objects, the following questions could be resolved:

Globular Clusters As galactic test particles (external motions) and as dynamical laboratories (internal motions), one can determine equipartition and tidal disruption time scales via Galactic interactions, characterize isotropic and anisotropy profiles in the clusters, ie. determine the 3-d velocity vector completely, and finally look in much more detail at cluster binaries and their role in the evolution of the clusters and their approach to energy equipartition. Parallaxes will dramatically improve the ability to compare observations of these systems with the predictions of Stellar Evolution.

Open Clusters In addition to the issues summarized above for Globular Clusters, all of which are relevant here, these objects are also fundamental distance calibrators. While they are likely to be supplanted in that role, it is important to resolve the inconsistencies that will certainly arise.

Interstellar Clouds Distances to members and background objects will illuminate the role of clouds as spiral arm tracers and as mass concentrations which affect motions within the galaxy. These objects are also important tracers of abundance variations in space and time in the Galaxy.

Star Forming Regions In addition to determining reliable masses for a number of pre-main sequence objects, the dynamics of star forming regions could be probed which would provide important clues to the processes that initiate (and terminate) star formation.

Dark Matter Components Stellar motions at large distances from the Galactic plane and Galactic center will substantially constrain the distribution of dark matter in the Galaxy and from that potentially the properties of MACHOs and/or WIMPs.

3.5 Galactic Questions

The Galactic science enabled by either 5 or 1 microarcsecond astrometry is fundamental to understanding an extraordinary array of basic astrophysical questions that go to the heart of our understanding of stellar and galactic structure and evolution. The distances and velocities to carefully choosen groups of objects will allow us to establish the dynamical state and evolution of the Galaxy with some precision. We will be able to characterize both the dynamical nature of spiral arm features and measure their true densities. Other features of the Galactic disk, particularly the warps that have been suggested and the variations in scale height with distance from the center can be confirmed and characterized.

As indicated above, the role of dark matter in the Galaxy's dynamics and much improved constraints on the nature of dark matter will come from detailed investigation of the kinematics of the disk high above the plane, and of the characterization of the optical rotation curve at increased distances from the center. A related question concerns whether the dark matter has a triaxial, spherical, or spheroidal distribution.

Studies of objects near the center of the Galacy will indicate the degree of central concentration of matter, providing important constraints on whether there is a massive collapsed object there.

3.6 Cosmological Constituents

Again, looking at Table 1, we see that for the nearest galaxies (the Large and Small Magellanic Clouds), only the supergiants will be detectable by "short exposures". However, dwarfs earlier than A2 and all giants will be accessible with the longer integrations. The parallax will be detectable at the 25% level, global motions will be measurable at the 1% level, and internal motions should be measurable to the 5% level. These accuracies would suffice to examine such issues as the extent of tidal disruptions from interactions with the Milky Way, while the dynamics should substantially constrain the mass distribution (which would be well defined if 1 μas accuracy is achieved) and the orbits of the Clouds around the Galaxy will be defined.

The Draco dwarf spheroidal system will be observable at a similiar accuracy level. Here, we could measure with some assurance the mass/light ratio of the system, verify the presence of dark matter, and look at the velocity distribution in a way similiar to the globular clusters.

M31 will not have a measurable parallax. However, the global motion should be measurable at the 5% level, and the rotation should be measurable at the 20%/star level. The global motions in particular will be important, leading to a dynamical age (the "timing" argument) for the Local Group. Only the brightest non-stellar point sources qualify for "short exposure" observations, while many bright supergiants will be accessible to the longer exposures.

For nearby Seyferts (10 Mpc) and the Virgo Cluster of Galaxies (16 Mpc), internal motions or changes in the structure of internal "knots" in jets and "hot spots" in the nuclear regions may be detected over the course of the mission.

3.7 Cosmological Questions

3.7.1 The Age of the Universe

Determination of the age of the Universe depends on our knowledge of the expansion rate of the universe and to a lesser extent, on the question of whether the universe is open or closed. The basic determination of the expansion rate (The Hubble Constant) depends on the knowledge of the distance scale. Also dependent on the distance scale is the determination of whether the universe is "open" or "closed", so the "Cosmic Distance Scale" is fundamental to our basic understanding of the global nature in time and space of the universe we live in. As with most physical characteristics, knowledge of the expansion rate depends on the conversion of a measurable: the rate at which galaxies are moving away from us as a function of their *apparent magnitude*, or some other measurable parameter, to some physical quantity. In this case the problem is the conversion of the apparent magnitude to absolute magnitude, ie., the distance.

3.7.2 Primordial Helium Abundance

The measured elemental abundances of metal poor stars indicate that the distribution of heavy elements from the big bang may not be what current theory predicts. The observed motions of the metal poor stars are indicators of their age, and hence their likelihood of being true carriers of primordial abundances. Accurate parallaxes to these stars is required to verify their galactic orbits, which would be consistent or inconsistent with formation in the early stages of the Galaxy's formation. If they were formed in the early stages of the galaxy, there are apparent conflicts with models of early nucleosynthesis in the universe.

3.7.3 Is the Universe Open or Closed?

Derivation of the extent and nature of the dark matter in the universe, and whether or not it is confined to galaxies, and in what manner, such as cold dark matter confined to the disk, or "left in the halo" during the formation of the galaxy, will ultimately determine whether or not the universe is closed. That is, it will determine whether the density of the matter in the universe is sufficient to cause the expansion to stop and reverse itself. The issue of the Galaxy's dark matter content was discussed above.

3.7.4 Age of Globular Clusters vs. the Age of the Universe

Currently, some determinations of the age of the universe (10 Billion years) conflict with some determinations for the age of the oldest globular clusters (15-20 Billion years). If these younger ages are verified through more accurate observations, then the theories of stellar evolution or the basic assumptions about the nature of the universe must be wrong. Therefore, both the determination of the age of the universe and the determination of the ages of the globular clusters must be reexamined with the utmost care.

This problem can be attacked both directly, through direct determinations of the distances of several key globular clusters, and by substantially improving our knowledge of the luminosities of the RR Lyrae stars and subdwarfs that currently serve to calibrate the distances. A detailed discussion of what is involved in each of these cases is given in Section 4.

3.7.5 Distance Scale

Distances, starting with the nearest stars and progressing to the most distant galaxies and quasars, form the basis for converting observed properties of objects (apparent magnitude, angular motions) into real physical properties (luminosities, velocities in km/sec). Until the advent of milliarcsecond parallaxes, accurate knowledge of distances of stars was limited to 10 to 20 parsecs. With current ground-based techniques, relatively few milliarcsecond parallaxes are measured routinely. Hipparcos will provide milliarcsecond parallaxes for about 100,000 stars. However, that only carries parallaxes known to 10% out to 100 pc, and parallaxes known to 1% out to 10 pc. For many astrophysical problems, eliminating a significant contribution from the parallax uncertainty requires a 1% error or better, a precision not yet obtained under the best of circumstances.

Beyond the limit of accurate parallax measurements, indirect secondary and tertiary methods must be employed. For example, to determine the luminosities of a variety of types of stars, the distance to a cluster needs to be determined. The Hyades Cluster is the closest well defined cluster with a consistent membership. It has been one of the standard distance calibrators for three quarters of a century. The Hipparcos determination will be limited to the grid "lock-up" errors, approximately 5% in distance, which will marginally improve the situation. SIM will allow its distance and three-dimensional structure to be determined at better than 1%.

Another set of distance calibrators are the RR Lyrae and Cepheid variable stars. Their absolute magnitudes (luminosities) are directly related to their periods and chemical compositions. The RR Lyrae stars are of nearly constant luminosity, and the Cepheids show a definite period- luminosity relationship. However, only a few of these stars are close enough to have their parallaxes measured directly, and those inaccurately. The distances to the RR Lyrae stars have been inferred through indirect calibration using statistical properties of their motions while cluster mainsequence fitting distances are used for Cepheids that are members of open clusters. The metallicity depencence of the Cepheid P-L relation has not been well determined and is very controversial. SIM will measure the distances directly to a large subset of these stars to the 1% level, including objects covering a range of metallicities.

The ultimate goal is to find distance indicators that can be used at very large distances; in the case of the Hubble constant, at distances where random velocities will be a small fraction of the expansion velocity. This involves calibrating a number of "tertiary" distance indicators, including the planetary nebulae luminosity function indicator, the surface brightness fluctuation indicator, SN Ia absolute magnitudes, and the Tully-Fisher method. These can be done by determining distances to nearby galaxies using RR Lyrae and Cepheid members, as described above. The situation as it currently stands is compared to what will be available with direct parallax measurements by the SIM in Figure 3.

Alternatively, rotational parallaxes (determined kinematically from the nearly circular rotation of bright Population I objects in spirals, cf. Section 4) to a number of nearby spirals and the extension by the Hubble Space Telescope of Cepheid distances out to Virgo may prove reliable enough to calibrate these latter distance indicators even more directly.

3.8 Conclusion

Even with 5 microarcsecond astrometric capability, SIM will enable an amazing range of fundamental astronomical science, from the probing of space for Jupiter-like planets out to 200 pc, to distinguishing between various theories of gravity. It will enable the determination

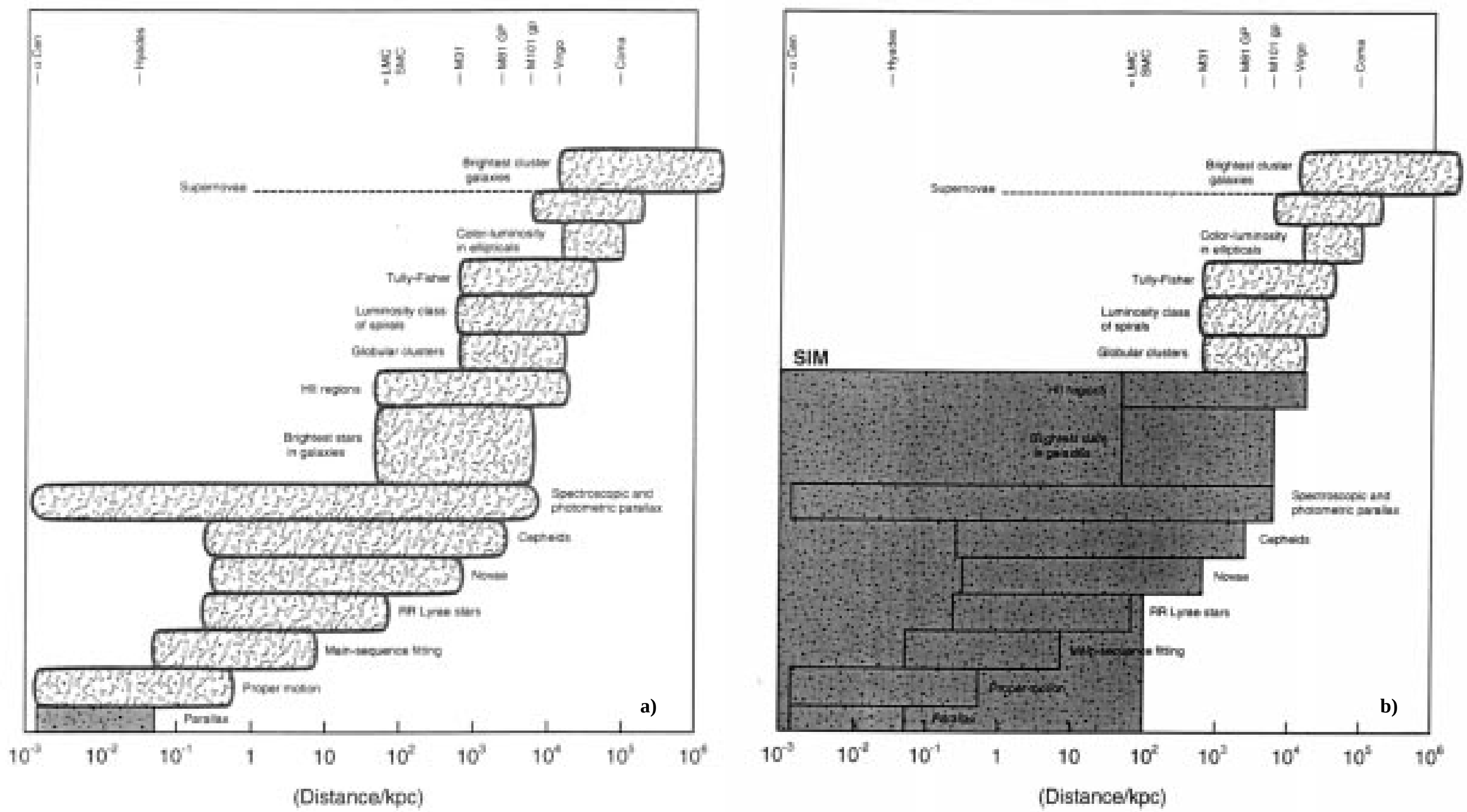

Figure 3. The steps to the Cosmic Distance Scale (after Rowan-Robinson) showing the various rungs in the ladder. Indicated are the "bedrock" layers, i.e., distance indicators that are directly calibrated with parallaxes, while the "sandstone" layers must be calibrated indirectly. Fig. 3a) shows the situation through Hipparcos while Fig. 3b) shows the gain promised by SIM, where all the secondary indicators currently in use and some of the tertiery are calibrated by direct parallax measurements.

of the age of the universe and will also resolve fundamental questions about the nature of the universe and our understanding of stellar evolution.

One issue not mentioned is serendipity. Because of the pointed nature of the SIM instrument, it is unlikely that truly "new" objects will be discovered. However, with the nearly 3-order-of-magnitude gain in measurement accuracy, we will find answers to questions that we did not ask. In turn, with the pointed instrument we will be able to pursue these unexpected turns as soon as preliminary reductions provide the hints. With such an extreme gain in accuracy, it is not possible to imagine what the discoveries will be, but it is clear that SIM's capabilities will touch most areas of astrophysics. These measurements will significantly enhance our understanding of the processes within the objects observed and with that understanding will come a deeper appreciation for the universe in which we live.

4 The Strawman Science Proposal: An Astrometric Science Sampler

4.1 Introduction

This science sampler provides examples of scientific programs that are achievable with the capabilities specified for an AIM and are of broad interest to optical astronomers and astrophysicists. These examples typify the scientific challenges discussed by the Bahcall report, where spatial resolution is described as the next frontier for optical astronomy. In addition, several new scientific goals for astrometry are identified that take advantage of the anticipated very large improvement over current capabilities.

While not a complete mission profile, these few examples of science problems illustrate what could be attacked within the context of an astrometric mission. And, while space astrometry has great potential for discovering other planetary systems, this topic is not addressed in these scientific examples; the search for extrasolar planets is the primary mission of NASA's ExNPS program for which SIM serves as a technical proving ground.

Seven possible projects are discussed in the sections below and are representative of what is feasible over a 5 year mission. These include:

1. Evolution of interacting binary systems leading to masses of black hole and white dwarf systems, and the identification of pulsar, supernova, and x-ray binary progenitors.

2. Stellar luminosities of massive stars, novae, nova-like variables, planetary nebulae, and Cepheids for which distances are otherwise difficult or impossible to measure directly.

3. Trigonometric parallaxes and a refinement of the cluster-Universe age problem by determining accurate distances to globular clusters, RR Lyrae stars, and field subdwarfs.

4. Dynamics of small stellar systems, proper motions in clusters and dwarf spheroidal galaxies as constraints on mass-to-light ratios, and orbital determinations for spectroscopic and x-ray binaries in globular clusters.

5. Stellar dynamics of the Galaxy to evaluate theories of density wave formation, the presence of dark matter in the disk, the rise or fall of the rotation curve at large Galactocentric distances, and the velocity dispersion of the outer halo.

6. Astrometry of AGNs to discern the internal structure of the emission-line regions, to detect proper motions within clusters of galaxies, and to test the likelihood of microlensing of AGN nuclei.

7. Rotational parallaxes: distances to nearby galaxies can be measured geometrically out to a few Mpc by observing the angular proper motion component of galaxy rotation and equating this to the measured circular velocity.

Note that in these examples and in the section that follows describing illustrative imaging projects, we identify the contributors. This is not intended to provide early "ownership" of those projects, but to recognize the extra depth to which these issues have been researched and to give appropriate credit for those efforts.

4.2 Evolution of Interacting Binary Systems

Chris Martin and Charles Bailyn, *Space Interferometry Science Working Group*

4.2.1 Motivation

Binary star systems which contain at least one compact object (white dwarf, neutron star, or black hole) provide extraordinary laboratories for exploring physical conditions unobtainable on Earth. Studies of the current binary parameters of such systems have provided the strongest evidence yet obtained for the existence of black holes and of gravitational wave radiation. The evolution of these systems is complex, due to the effects of mass transfer and mass loss. The origin of Type I supernovae, millisecond pulsars, low mass x-ray binaries, and globular cluster x-ray sources all involve unsolved issues in the evolution of compact binary systems. The combination of excellent spatial resolution and high sensitivity will enable AIM to determine the orbital parameters of these systems to unprecedented accuracy. The current dearth of definitive mass and orbit determinations suggests that even a modest number of AIM measurements will represent a breakthrough in this field.

Single stars can be parameterized by three parameters (M, t, and Z), but binary systems require at least seven (M_1, M_2, t_1, t_2, a, ϵ, Z). In interacting binaries with compact primaries, mass transfer and mass loss vastly increase the complexity of these systems. Thus it is impossible to place any particular system in its evolutionary context without accurate knowledge of the stellar masses and orbital separation a. In compact binaries, the radial velocity of the secondary can sometimes be used to obtain the mass function $f(M) = (M_2 sin\ i)^3/(M_1 + M_2)^2$. AIM can provide a measurement of the inclination i and the orbital separation by measuring the motion of the center of light. Thus AIM will enable us to determine the masses of the components of these systems, which is the crucial parameter for a variety of problems. Such a measurement cannot be performed on the ground in these short period, compact, and often distant systems.

Cataclysmic variables (CVs) will display easily detectable orbital motions, providing an accurate determination of the white dwarf primary mass. While the orbital motion of the most compact low mass x-ray binaries (LMXRB) will be difficult to measure with AIM, the globular cluster x-ray sources may have higher mass primaries. AIM could also discover the presence of tertiary stars in hierarchical triple systems, an important clue to the formation of globular cluster x-ray sources, millisecond pulsars, and galactic bulge x-ray sources. While interacting binaries circularize quickly, newly formed neutron stars in Be star x-ray binaries are often in eccentric orbits which hold clues to the supernova explosion dynamics and the kinematics of isolated neutron stars.

Specifically AIM has the potential to provide unique insight into these important questions:

1. What is the mass of the primary in candidate black hole systems? What is the distribution of black hole masses, and can this be reconciled with the evolution of high mass stars?

2. How are millisecond pulsars in and out of globular clusters formed? From low mass x-ray binaries? Or by accretion-induced collapse of white dwarfs in binaries?

3. What is the origin of Type I supernovae?

4. What are the precursors to low mass x-ray binaries? Are they formed by accretion induced collapse of white dwarfs in binaries?

5. Do white dwarfs with masses near the Chandrasekhar limit in binary systems exist in sufficient numbers to account for Type I supernovae and/or low mass x-ray binaries and/or millisecond pulsars?

6. How are globular cluster x-ray sources formed? What is their relationship to millisecond pulsars?

7. How many globular cluster x-ray sources and low mass x-ray binaries are members of hierarchichal triples?

8. What is the kinematics of low mass x-ray binaries? Globular cluster x-ray sources? Can the LMXRB be formed by disruption or ejection from globular clusters?

9. How is accretion driven in each system: secondary evolution, magnetic braking, mass and angular momentum loss? What is the evolutionary state of the secondary?

10. How does the mass distribution of neutron stars in low mass x-ray binaries compare with that of high mass x-ray binaries? How does this reflect on the origin of low mass x-ray binary systems?

4.2.2 Science Program

Stellar Masses. For each system, determination of its evolutionary status requires an unambiguous measurement of the primary and secondary masses, and of the orbital elements. Compact binaries will be unresolved by AIM, but the fringe shift due to orbital motion will follow the *center of light* of the binary. The maximum angular motion of the center of light (for a circular orbit) is

$$\alpha = 40\ \mu''\ M_1^{1/3}(1+q)^{-2/3}[\frac{l-q}{l+1}]P_{day}^{2/3}D_{kpc}^{-1},$$

where M_1 is the primary mass, $q = M_2/M_1$, P_{day} is the orbital period in days, and D_{kpc} is the distance in kpc (obtained from parallax). The ratio of fluxes due to the two stars is $l = F_2/F_1$. Note that the center of light coincides with the center of mass when $q = l$, and there is no apparent proper motion.

AIM can measure α, D, and the orbital inclination i. Generally l can be determined to reasonable accuracy in most systems from spectroscopy. For cataclysmic variables and low-mass x-ray binaries, $l < 1$ usually holds. For high mass x-ray binaries $l > 1$. In many systems, particularly cataclysmic variables, the inclusion of two bands in the red and in the

UV would permit separate measurement of the orbital radii of the two stars. Otherwise, assuming l is known, one parameter of the pair M_1, M_2 can only be determined as a function of the other. The ambiguity is removed if (i) the secondary star can be spectroscopically classified; (ii) roche lobe accretion can be assumed; or (iii) the secondary radial velocity can be measured.

Assuming that the secondary mass can be determined, the error in the derived primary mass is roughly

$$\frac{\Delta M_1}{M_1} \simeq -(\frac{1+q}{5/3+q})\frac{\Delta\alpha}{\alpha} + (\frac{1+q/3}{5/3+q})\frac{\Delta M_2}{M_2},$$

since the error in the distance and period will be small. For low mass ratios, $\Delta M_1/M_1 \simeq 3/5(\Delta\alpha/\alpha + \Delta M_2/M_2)$

Black Hole Masses. While several black hole candidate x-ray binaries are known, radial velocities yield only lower limits on the mass of the compact primary. Currently, GRO is discovering new candidates at the rate of ≈ 1 per year, so a population of a dozen or so strong candidates would be available to AIM. AIM can furnish definitive black hole masses and the beginnings of a black hole mass distribution by measuring orbital separation and inclination. This would provide a critical test for black hole formation models. The bright secondary and wide orbits of some of the galactic black hole candidates facilitate measurement by AIM.

White Dwarf Masses. If accretion onto white dwarfs past the Chandrasekhar limit leads to Type I supernovae, millisecond pulsars or low mass x-ray binaries, then a significant fraction of accreting white dwarf binaries should have high mass primaries. If CVs are the progenitors, and accretion rates are constant in time, then >10% of them should have white dwarfs in the mass range 1.2-1.4$M_\odot$. AIM can make a start on a meaningful mass distribution with ~30 definitive white dwarf mass measurements. CVs are typically moderately bright (12<V<15) and nearby, with separations in the 30-50 μas range. A 10% measurement of α ($\sigma < 3\,\mu$as) leads to a 6% error in M_1.

Hierarchichal Triples and Binary Kinematics. At least one pulsar in a globular cluster (PSR 1620-26) is known to be a member of a hierarchical triple system. The optical counterpart of the tertiary has recently been shown to be a 20th magnitude main sequence star. Other globular cluster and/or low mass x-ray binary sources may also be members of hierarchichal triples. These could result from three body interactions leading to the formation of a compact binary. Thus the nature and orbit of the third body in the system may reveal crucial information regarding the formation of the systems in general. The imminent discovery of more optical counterparts with HST is likely to provide suitable targets for other globular cluster sources. While measurement of the orbital motion of the compact binary in these systems will be very difficult with AIM (although possible with two or three of the highest mass systems), motion due to a third companion should be observable. Faint optical counterparts (V$\sim$ 17-20 in galactic systems, V $\gtrsim$ 20 in globular clusters) and crowded fields make this a challenging measurement. A beginning program would observe five bulge sources and five globular cluster sources. In addition, secular proper motion measurements would give kinematic data for the binaries in and out of clusters. This will provide important constraints on the progenitor population, binary formation mechanisms, and the relationship between globular cluster binaries and those in the galactic bulge.

Be Star X-ray Binaries. Be star x-ray binaries are believed to consist of a recently formed neutron star and a Be star companion. The orbit has not yet circularized, and the eccentric motion produces periodic eruptions at periastron as the compact star passes through the mass outflow from the Be star. Measurement of the orbital parameters would yield information on the anisotropy of the supernova mass ejection. It is important to relate this to the kinematics of isolated pulsars, and to the physics of the explosion.

4.2.3 Observing Program

Table 2 lists a selection of typical objects in each class that would form part of the observing program. The table shows magnitudes, distances, orbital periods, estimated masses, and predicted orbital angular separations. In Table 3, we present a rough outline for an observing program, with typical magnitudes, required astrometric accuracies ($\Delta\alpha$), number of objects in each class and number of measurements per object.

Table 2: A Selection of Candidate Objects

Type	Typical Objects	V	D(kpc)	P(orb)	M_1	M_2	$\alpha(\mu as)$
CV	Z Cam	11.5	0.25	7h	1.2	0.9	23
	U Gem	14	0.08	4.0h	1.1	0.5	45
	SS Cyg	12	0.15	6.5h	1.3	0.8	30
BHC	Cyg X-1	9	2.5	5.6d	10?	10	170
	V404 Cyg	12-18	2–3	6.5d	>6.3	0.8	>90
	A0620-00	18	1-2	0.3d	>3.0	0.5	>15
	GU Mus	20	2-3	0.4d	>2.9	0.5	>6
LMXRB	Cyg X-2	14.6	9.8d	8	1.4?	~2	15
	Her X-1	13	5	1.7d	1.4	1	8
	Sco X-1	12	0.7	0.8d	1.4	0.5	7
	Cen X-4	19-13	1.5	8.2h?	1.4?	0.7	4
Be Star	V635 Cas	15	3	24d	1.4	10	33
LMXRB	V691 CrA	15.4	>0.6	5.6h	1.4?	0.7	<8
upper limits	V1055 Ori	18.5	6	4.9d	1.4?	<0.5	<5
	V1727 Cyg	16.4	2.2	5.2h	1.4?	<0.5	<1.5
	V926 Sco	17.5	7	4h	1.4?	<0.5	<0.4
	4U1626-67	19	10	0.75h	1.4	0.1–0.3	.02–.06
cluster triple	PSR1620-26	20	2	$\gtrsim$ 5yr	1.6	0.45	1800

Table 3: Candidate Observing Program

Type	V	P	$\alpha(\mu as)$	$\Delta\alpha(\mu as)$	# Obj	# Meas/Obj	Goals
CVs	14	2-20h	30	3	30	10	1
LMXRB	18	6h-9d,10-1000d	5-300	1-3	5	5	2,3,6
Globular	15-22	10-2000d	6-2000	3-20	5	5	2,3,6
BHC	10-18	6d	5-200	2-10	10	10	4
Be Star	10-15	10-30d	20-40	3	2	10	5

Goals:

1) Orbital elements: white dwarf mass distribution
2) Orbital motion due to tertiary in hierarchichal triple
3) Proper motion; kinematics of low mass binaries
4) Orbital elements: black hole mass distribution
5) Eccentric orbital elements; dynamics of SN explosion
6) Binary orbital motion (if possible): neutron star masses

4.3 Stellar Luminosities

Steve Ridgway, *Space Interferometry Science Working Group*

The observational determination of stellar luminosities is generally quite difficult. As conventional astrometry is limited to distances of a few hundred parsecs, it has been most useful for study of the well populated part of the main sequence. For many stellar types which are relatively rare, parallax measurements have not been very useful. Indirect indicators, often statistical inference, have been commonly used to estimate stellar distances.

The availability of a facility for measurement of parallaxes to microarcsecond precision would extend direct distance determination to most stellar types. A precision of 30 microarcsec would reach to 3 kpc with 10% accuracy, and 3 microarcsec would reach most of the galaxy, including the galactic center.

4.3.1 Massive stars

The most massive stars spend most of their short lives as H-burning O-type stars. Although only a tiny fraction (10^{-7}) of the stars in the Galaxy are more massive than $20M_\odot$, these stars play an important role in galactic structure and evolution.

However, the absolute magnitude scale of O stars is poorly determined. As recently discussed by L. Divan and M.-L. Burnichon-Prevot (1988 in O Stars and Wolf-Rayet Stars, eds. Conti and Underhill, NASA SP-497, p. 47), no O star is sufficiently close to the sun to have a trigonometric parallax. Instead, the absolute visual magnitudes come primarily from O stars in clusters and OB associations whose distances are determined primarily on the basis of the early B-stars (Conti, Garmany, deLoore and Vanbeveren 1983 ApJ 274, 302 and references therein). However, the distances of these clusters and associations are clearly uncertain in and of themselves; see for example, Garmany and Stencel (1992, A&AS, 94, 211).

Although the determination of the bolometric correction for these hot stars adds a major uncertainty in determining their overall luminosity, the uncertainity in the spectral-type, absolute visual magnitude calibration is equally great at present. Accurate knowledge of the luminosity of these stars is important for: (1) comparing masses derived from stellar evolutionary models with those implied by stellar atmosphere codes, (2) determining initial mass functions, and (3) studying stellar evolution at the high mass end of the HRD.

Typical distances to OB associations and clusters containing O stars are 1-2 kpc. Typical apparent magnitudes are V=4-6.

4.3.2 Novae

The shell expansion velocity method of distance determination can only be applied decades after eruption, and is then limited by uncertainties about optical depth (Duerbach, PASP 93, 165, 1981). Other techniques are less direct and less reliable. Most detected galactic novae are brighter than V=12 at maximum, but in the months required to obtain a parallax result novae will fade by several magnitudes. A measurement capability to V=18 would cover most newly discovered galactic novae and many which erupted in recent decades.

4.3.3 Nova-like Variables

These stars include past or potential novae in a quiescent stage, non-novae which experience an accretion induced outburst, and stars with with an evolutionary relation to novae. UX U Ma stars, dwarf novae, AM Her stars, symbiotic stars, and all types of cataclysmic binaries are included (Vogt 1989, in Classical Novae, Bode and Evans, eds). (The evolution of CV's and other interacting binary systems is discussed in section 1.) Sorting out the outburst mechanisms in these stellar types is a challenge. Accurate luminosities are needed to distinguish among alternate possible energy generation mechanisms. At present, uncertainties of 50% in luminosity are typical of the best-determined cases. Astrometric precision of 30 microarcsec and a limiting magnitude of 15 would suffice to determine luminosities of the 40 brightest.

4.3.4 Planetary Nebulae

Determination of distances is the fundamental problem for study of planetary nebulae, and no satisfactory method exists (Kaler, Ann.Rev.A.A. 23, 89, 1985). The problem has become even more significant since work of the last decade has shown that planetary nebulae appear to be a good distance indicator, with a narrow mass range for the remnant stars (Jacoby, Ap.J. 339, 39, 1989). Direct determination of distances for galactic planetary nebulae (using the parallax of the central stars) would lead to significant progress in the understanding of the formation and evolution of the shells, the status of the central stars, and the role of these objects as standard candles.

It is important to observe PN's over a large range in galactocentric distance. Dramatic progress could be achieved with astrometric precision of 10 microarcsec for study of the central stars to limiting magnitude of V=18.

4.3.5 Cepheids

Cepheids are intermediate to massive stars in the core helium burning phase which are unstable against radial pulsation. In addition to the importance of these stars to stellar structure and evolution, Cepheids form the cornerstone of the extragalactic distance scale. A sample of 21 closest Galactic Cepheids with periods exceeding 10 days is the most important for this purpose. The V magnitudes of these stars are less than 10. The parallaxes of 19 of them lie between 0.2 and 1.0 mas, and should be measured to 5% accuracy.

4.3.6 Observing program

A possible observing program is summarized in Table 4. An accuracy of 5% is required for single objects.

Table 4: Possible Selection of Objects

Type	V	$\alpha(\mu$as)	$\Delta\alpha(\mu$as)	# of objects
Massive Stars	4-6	500-1000	25-50	20
Novae	18	100-200	5-10	20
Nova-like variables	11-15	300-1000	15-50	20
Planetary Nebulae	12-16	100-1000	5-50	40
Cepheids	10	200-1000	10-50	20

What are the implications for AIM observations of the following special conditions which apply to these sources?

1. Many of these sources will be concentrated in the galactic plane and towards the galactic center.

2. The shells of planetary nebulae and novae should not disturb observations of the central star if the shells are large and optically thin. However, young shells with apparent diameters of order an arc-second or less, may be optically thick, and have approximately a uniform disk appearance even in the continuum. Will it still be possible to make parallax determinations? (Assume the shell does not change shape during the observation series.)

3. The O-stars within several kilo-parsecs are very bright (V=4-6).

4.4 Trigonometric Parallaxes and the Cluster-Universe age problem

Paul Hemenway, *Space Interferometry Science Working Group*

4.4.1 Motivation

Clusters in general and globular clusters in particular are test particles with unique ages and initial chemical compositions that can be used to trace the development of the formation of the Milky Way, and test our theories of stellar evolution at the same time. While these two functions have been recognized for a long time, the combination of them to determine the ages of globular clusters as a function of metallicity, for example, has led to a possible discrepancy with the age of the Universe: Some age determinations of the metal- poor globulars result in ages that are older than some ages determined for the Universe. Whether or not significant age differences exist among the globulars in the Milky Way is still a question, partly because of inaccuracies of the various measurements that go into fitting a real globular to a theoretical model, and partly to our uncertainties in the theoretical models, due to effects such as diffusion in the core complicating the evolution itself, and diffusion in the atmosphere complicating the abundance analyses.

The determination of the ages of the globular clusters relies on several steps, but the crux of the observational problem is determining the turn-off point of the main sequence, which should be only a function of the mass of the stars at that point, their initial chemical composition, and their age. In order to determine the turnoff point, the absolute magnitude of the main sequence must be determined. For example, a difference of 10^9 years corresponds to an absolute magnitude difference of 0.063 magnitudes. Therefore, if the absolute ages are to be accurate to a billion years, the contribution to the error from the parallax determination of the cluster must be significantly less than 0.063 magnitudes in the distance modulus, or significantly less than 3% in the parallax. Therefore, the intent of this proposal is to measure the parallaxes of objects which will allow the determination of the distance of a number of globular clusters in the galaxy to the 3% level rms individually or the 1% level in the fitting of the main sequence.

4.4.2 Science Program

The three groups of objects considered are:

1. The parallaxes of the globular clusters themselves,
2. the RR Lyrae field stars which are used to determine the absolute magnitudes of the horizontal branchs (HB) of the globulars, and, finally,
3. the "subdwarfs" which are used to define the absolute magnitude of the main sequences of the globulars.

4.4.3 Globulars Themselves

Parameters for selected globular clusters are reported in Table 5.

Table 5: Globular Clusters

Cluster	6th Brightest star (m_{pg})	distance mod (mag)	distance (kpc)	% error in parallax at 30 μas	at 10 μas
NGC104 (47Tuc)	12.4	13.46	4.92	14.8	4.9
288	14.5	14.7	8.71	26.1	8.7
3201	13.3	14.15	6.76	20.3	6.8
5053	15.1	16	15.85	47.6	15.9
5139 (ω Cen)	12.6	13.92	6.08	18.2	6.1
5272 (M3)	13.92	15	10.00	30.0	10.0
5904 (M5)	13.74	14.51	7.98	23.9	8.0
6205 (M13)	13.45	14.35	7.41	22.2	7.4
6341 (M92)	13.6	14.5	7.94	23.8	7.9
6397	11.9	12.3	2.88	8.7	2.9
6752	12.8	13.2	4.37	13.1	4.4
6838(M71)	nd	13.9	6.03	18.1	6.0
7078(M15)	14.13	15.26	11.27	33.8	11.3
7099(M30)	13.77	14.53	8.05	24.2	8.1
Pal 12	nd	16.2	17.38	52.1	17.4
open:NGC188	nd	11.13	1.68	5.1	1.7

(Mostly from vandenBerg, 1983, ApJ Sup., 51, pp. 29-66)

4.4.4 Field RR Lyrae calibration

NB: an error of 0.022 mag in the distance modulus is equivalent to 1% error in the parallax.

The 20 brightest field RR Lyrae stars range from 7.66 mean-light V to about 10.0. (Hemenway, AJ, 1975, *e.g.*,) Those extremes are represented in Table 6.

The trigonometric parallaxes of the n-brightest (closest) RR Lyrae stars must be determined in order to calibrate the absolute magnitude as a function of period, and metallicity if the relation between the field and cluster RR Lyrae stars it to be used at the 1% level.

4.4.5 The field subdwarfs

Carney (Highlights of Astronomy, vol 6.,1983) gives 90 subdwarfs ranging in magnitude from 7.24 to 12.0. The range in B-V is 0.37 to 0.76.

The range of Carney's 90 subdwarfs could give an excellent calibration of the subdwarf sequence to which the globular cluster main sequences could be fit. The problem would be transferred to the relationships between the physical parameters and the observed parameters, about which a great deal has been discussed, and certainly more will be needed before we understand the absolute ages of the clusters at the billion year level of accuracy.

Table 6: RR Lyrae stars

Type of star	$\langle V \rangle$ (mag)	distance mod (mag)	distance (kpc)	% error in parallax at 30 μas	at 10 μas
RR Lyrae	7.66	7.06	0.26	0.77	0.26
V Ind	9.91	9.31	0.73	2.2	0.73
RV Leo, *e.g.*,	14	13.4	4.79	14.4	4.8

Table 7: Field Subdwarfs

Subdwarf	V (mag)	B-V (mag)	Mv (mag)	distance mod (mag)	distance (kpc)	% error in parallax at 30 μas	at 10 μas
Bright-blue	7.24	0.37	4.7222	2.5178	0.03	0.10	0.03
Bright-red	7.24	0.76	6.6956	0.5444	0.01	0.04	0.01
Faint-blue	12	0.37	4.7222	7.2778	0.29	0.86	0.29
Faint-red	12	0.76	6.6956	5.3044	0.12	0.35	0.12

4.4.6 Observing Program

Three subprograms are proposed. All three subprograms would help determine the distances of the globular clusters in our galaxy for a variety of studies. Particular to this proposal is the role accurate distances would play in the absolute age determination of the globulars, including as a possible function of observed or inferred physical parameters. (The evidence for such a variation is weak or circumstantial at the moment, but could be significant at measuring accuracies below what is currently achievable.)

First is the measurement of the parallax of the nine brightest stars in each of 15 globular clusters. The magnitudes would range from 12 to 15. The expected accuracies would therefore be a factor of 3 better than the quoted error for a single parallax, aside from systematic effects. Because of the distances of the globulars, the direct parallax measurements would probably not provide the most reliable distance measurements until a significant number of parallaxes can be measured at the 10 microarcsec level.

The second program would be to measure the parallaxes of as many of the brightest RR Lyrae stars as possible, but a program of about 90 stars might be reasonable. Here the magnitudes range from 7.66 to 14.0. If the time and/or magnitude limitations are severe, a limited program of 20 stars down to the 10th magnitude would provide a calibration of the HB more accurate than is available from current statistical parallaxes.

The third program would measure the parallaxes of as many of the brightest 90 subdwarfs as possible. Current parallaxes of 7 or 8 subdwarfs are the fundamental calibration against which the main sequence of the globulars are fit to determine the absolute magnitude of the

MS turnoff. Again, if a time or magnitude limitation is imposed, the parallaxes of the "Great 8" would provide an interim solution. The stars are bright enough (7-12) and close enough so that the calibration of the absolute magnitude of the sample stars as a function of color, metallicity, and other parameters would be impeccable. The problem would then come in making the assumption that the subdwarfs are a representative sample of the globular cluster main sequence population at the level of accuracy of the Parallax Data or determining from physical observations and models exactly what is the relationship. But the question of the absolute magnitudes of the field subdwarfs would be unconditionally solved.

4.5 Dynamics of Small Stellar Systems

Jeremy Mould and S. George Djorgovski, *Space Interferometry Science Working Group*

Globular clusters provide an exquisite laboratory for studies of stellar dynamics. From them, we can learn about the physics of other stellar systems, *e.g.*, galactic nuclei, which (except for the few brightest stars in the nuclei of M31 and M32) will not be resolved into stars in any predictable future. Central relaxation times for globular clusters span a range from 10^5 to 10^{10} years, and median relaxation times from 10^8 to 10^{10} years, thus guaranteeing that a large range in their dynamical evolutionary states is present (cf. Djorgovski & Meylan 1994, AJ, 108, 1292).

One important problem involves the shape and evolution of a cluster's velocity anisotropy tensor, and the velocity distribution of stars in general. Scattering processes are expected to isotropize the orbits in the core, leading to a radial gradient in anisotropy. Stars are evaporated from the cluster, which also modifies the orbital statistics. Cluster motion in the Galaxy's tidal field and shocks from disk and/or bulge passages will drive the dynamical evolution in cluster envelopes. Globular clusters also evolve towards core collapse, which should also introduce dynamical signatures, as stars are being scattered out of the core by their interactions with the dominant hard binary. Finally, the residual effects of cluster formation conditions are expected to influence what we observe in a significant way, at least for the most massive systems.

The radial velocity dispersion profile which is currently observable spectroscopically cannot be interpreted unambiguously as an anisotropy profile, although there are strong suggestions of anisotropy in at least some clusters (cf. Meylan 1987, A&A, 184, 144). Astrometry, on the other hand, will yield information along the three axes of the velocity dispersion tensor and constrain dynamical models of globular clusters unequivocally.

A comparison of the best efforts on globular cluster internal motions from ground based astrometry shows that *rms* errors of 0.13 mas/yr are achievable (Cudworth & Monet 1979, AJ, 84, 774). Space interferometry is required to provide the next order of magnitude in accuracy, unless it can be shown that this is achievable from the ground.

Velocity distributions have traditionally been assumed to be Gaussian. However, recent discoveries of the so-called cannonball stars (high velocity stars which, by their location and photometry, appear to be cluster members but have radial velocities in excess of the escape velocity; see Meylan, Dubath, & Mayor 1991, ApJ, 383, 587) call this assumption into doubt. The nature of these objects remains a mystery; they may be ejected due to interactions with hard binaries. Obtaining their 3-d velocities would help understand their origin, and probe the strong scattering interactions deep in the cluster cores.

4.5.1 Cluster dynamics experiment

What we have in mind, therefore, is a program in which proper motions are measured for a set of 100 brightest stars in each of three strategically chosen clusters: 47 Tuc (NGC 104), M15 (NGC 7078), and NGC 6397. 47 Tuc is a massive, high-concentration system, with a resolved core. M15 is a classical post-core-collapse cluster, which may be in the state of a deep collapse right now. NGC 6397 is one of the nearest globulars, also probably undergoing a post-core-collapse re-expansion.

With a sample of 100 stars, velocity dispersion will be determined with a fractional error of 7% (or 0.7 km/sec), and so we have set the desired measuring errors a factor of two lower than this statistical limit. The radial profiles of different components of the velocity dispersion tensor will then be compared with dynamical models. Also, it would be valuable to explore differences in dynamics between different stellar types (*e.g.*, the HB vs. the red giants).

For example, the brightest stars in 47 Tuc are V = 12, and these are the ones for which astrometry would be carried out. In the core, which has a surface brightness of approx 15 mag/arcsec^2, there are 0.03 stars/arcsec^2. The next magnitude has 0.2 stars/arcsec^2, and the next 0.4. This lumpy background may pose a problem for interferometers. The cluster distance is 4.6 kpc. The central radial velocity dispersion is 11.5 km/sec. Stellar velocities can then be determined each to an accuracy of 0.3 km/sec (15 μas/yr). M15 is 10.5 kpc away, has a slightly larger central velocity dispersion, and so the accuracy of spatial velocities would be half as good, but still quite adequate. NGC 6397 is only 2.2 kpc away, but its central velocity dispersion is half that of 47 Tuc.

4.5.2 Spectroscopic binaries experiment

Binaries are now thought to be of major importance in the global dynamics of globular clusters. For reviews, see, *e.g.*, Bailyn (1993, ASPCS, 50, 191), Goodman (1993, ASPCS, 50, 87), or McMillan (1993, ASPCS, 50, 171).

Spectroscopic binaries have been detected in globulars with amplitudes of tens of km/sec and periods of years. This implies separations of order one mas. We therefore envisage a secondary program of orbital determination of, say, 10 spectroscopic binaries of V = 17 mag in 47 Tuc.

More interesting objects involving binaries have also been detected in globulars, including x-ray sources and millisecond pulsars. Optical ID's of the former are now being obtained with the HST (see, *e.g.*, King *et al.* 1993, ApJ, 413, L117). X-ray sources are present in both M15 and NGC 6397 (see Grindlay 1993, ASPCS, 50, 285), and 47 Tuc has proved to be particularly rich in millisecond pulsars (cf. Phinney 1993, ASPCS, 50, 141, for a review), as well as blue stragglers (Paresce *et al.* 1991, Nature, 352, 297). Spectroscopy of the optical counterparts of some of these objects is now in progress with the HST, and from the ground.

Obtaining their spatial velocities, and if possible, mapping their orbits would be of a great astrophysical importance.

4.5.3 Dwarf spheroidal galaxy experiment

Dwarf spheroidal galaxies are a completely different type of a stellar system. Probably the most intriguing problem they pose is the nature and the amount of dark matter in them. They appear to have unusually high (M/L) ratios, which are anticorrelated with their luminosities, and approach 100 for the least luminous ones (Draco and Ursa Minor). For good reviews of the subject, see, *e.g.*, Pryor (1992, in Morphological and Physical Classification of Galaxies, eds. G. Longo *et al.*, p163, Dordrecht: Kluwer), or Da Costa (1992, in IAU Symp. 149, The Stellar Populations of Galaxies, eds. B. Barbuy & A. Renzini, p. 191, Dordrecht: Kluwer).

Velocity anisotropy could have an important effect on the derived (M/L) ratios, perhaps by a factor of two, although it probably cannot explain completely the extremely high values seen. Hints of velocity anisotropy, from the radial velocity measurements alone, have been seen in the Fornax dwarf (Mateo *et al.* 1991, AJ, 102, 914). Again, radial velocity measurements alone cannot unambiguously resolve this issue, and spatial velocities are necessary. The form of the velocity distribution may even be used to constrain the types of the dark matter in these systems, *e.g.*, possible massive black holes (Strobel & Lake 1994, ApJ, 424, L83). Spatial coherence (or a lack thereof) of velocities can be used to constrain models of these galaxies as being out of dynamical equilibrium, *e.g.*, due to the tidal effects of the Galaxy. Astrometry might yield a surprise here, for example by detecting streaming motions.

We thus propose an experiment similar to that described above for globular clusters, but for the Draco dwarf spheroidal galaxy. It is one of the two closest and highest (M/L) systems, the other being Ursa Minor. It is a much more difficult target than the globulars, due to its larger distance of 75 kpc. We anticipate that ground-based observations of Draco with large telescopes will determine the radial velocity dispersion profile and radial velocity distributions very well within the next decade. The brightest stars have V = 17. The radial velocity dispersion is 9 km/sec, and the central surface brightness is at least an order of magnitude below that of the zodiacal light. A sample of 50 stars measured to an *rms* error of 5 μas yr^{-1} would yield sufficient information to constrain the dynamical models, and illuminate the nature of the dark matter in dwarf galaxies.

4.5.4 Summary

1. Proper motions of 100 brightest stars each in 47 Tuc, M15, and NGC 6397
2. Orbital determination of 10 spectroscopic binaries in 47 Tuc
3. Proper motions and orbital determination for 6 x-ray binaries or other peculiar objects in our target clusters
4. Proper motions of 50 brightest stars in the Draco dwarf.

4.6 Stellar Dynamics of the Galaxy

Stefano Casertano, *Space Interferometry Science Working Group*

The following addresses possible astrometric experiments to probe the dynamics of the Galaxy. Among the many outstanding problems that accurate astrometry can usefully address, we have chosen four that appear to have a more direct impact on our knowledge of the kinematics, mass distribution, and history of the Galaxy and its stellar populations.

4.6.1 Spiral arms: density waves or not?

A long-standing controversy on the nature of spiral arms is whether they correspond to density enhancements in the background stellar distribution (Lin-Shu density waves) or to regions of enhanced star formation (Gerola-Seiden self-propagating star formation). If they are density waves, the amplitude of the density enhancement is an important diagnostic parameter for theories of formation of the spiral arms.

An astrometric mission can attack and solve this problem directly by measuring the kinematics of stars near the arm. If a density enhancement exists, it will affect the stellar motions in a characteristic way; the amplitude of the perturbation measures the density contrast between arm and interarm region. If no perturbation is observed, self-propagating star formation would receive a strong confirmation.

A project that could provide a definitive answer to this question could focus on the relatively close Perseus arm (about 2 kpc away). Stellar motions would be determined for stars near the arm, both foreground and background. Accurate parallaxes would be needed to determine on which side of the arm each star is. The project would include about 20-50 stars, typically of spectral class A and earlier (apparent magnitude V = 13 and brighter), within 200 pc of the arm. Parallaxes would be required with an accuracy of 2%, corresponding to about 10 μas, to place the star precisely with respect to the arm. Peculiar motions of order of 20 km s^{-1} are predicted by the density-wave theory; proper motions would be needed with an accuracy of 100 μas, corresponding to about 1 km s^{-1} in space velocity. Radial velocities should be obtained for these stars to complement the astrometric observations.

4.6.2 Dark matter within the disk: the Oort limit

Two recent programs have attempted to redetermine the surface density of the Galactic disk in the solar neighborhood. One, conducted by Bahcall and collaborators, finds evidence for dark matter in the disk. The other, due to Gilmore and Kuijken, finds none. The issue is very important because of the implications on the nature of dark matter: a substantial amount in the disk implies a dissipational character, which would rule out most non-baryonic candidates and many baryonic ones.

One important source of uncertainty in the Bahcall result, based on the distribution of K giants perpendicular to the galactic disk, is the error in the distances to individual stars. These are relatively bright objects (apparent magnitudes 10 and brighter); their distance scale could be recalibrated and substantially improved by direct parallax measurements of K giants with a range of metallicity estimates. We envisage about 20 parallax measurements of V = 10 stars with individual accuracy of about 50 μas, corresponding to a 5% error in distance at 1 kpc.

Space velocities for program stars would also improve the sample selection by confirming or ruling out the existence of separate kinematic subgroups, which also contributes to the final uncertainty in the results. The required accuracy is only a few hundred μas, but the number of stars would then be larger, of order of 100.

4.6.3 The rotation curve outside the solar circle

The rotation curve of the Milky Way inside the solar circle is accurately known from HI observations. These however cannot be used outside the solar circle because it is impossible to estimate accurately the distance to individual HI clouds. Current estimates of the rotation curve outside the Sun are based on stellar and CO data, and suffer from considerable uncertainty because of the distance scale. The existence and amount of dark matter near the Sun is *very* sensitive to the slope of the rotation curve near and just outside the solar circle.

The problem can be solved by selecting a number of disk stars near the plane, preferably early type, and measuring their distance and proper motion accurately. The stars should be distributed in a range of galactic longitudes, between $\ell = 120^o$ and $\ell = 240^o$.

A project to determine the rotation curve between 8 and 15 kpc would include 50 B stars at a maximum distance of about 10 kpc, for apparent magnitudes V = 12 and brighter. Distances are needed with an accuracy of 10%, so a parallax accuracy of 10 μas is required. Proper motions are needed with an individual accuracy of about 10 km s^{-1}, which implies proper motion accuracy of 200 μas yr^{-1}. Radial velocities should be obtained for these stars as well.

4.6.4 Kinematics of the outer halo

The kinematics of halo stars has important implications on both the formation history and the mass distribution of the Galaxy. As expected, halo stars have a large vertical velocity dispersion, about 90 km s^{-1} at 6 kpc. However, at larger distances, the velocity dispersion seems to decline, and a value of 60 km s^{-1} has been measured at about 25 kpc from the plane. The interpretation of this interesting observation is difficult because only one component of the velocity dispersion is measured. Knowledge of the other two components, which can be measured using proper motions, will discriminate between two very different possibilities: a change in the orbital structure of the Galaxy, with interesting implications on the separability of the potential and the existence of a third integral of the motion, and a true decrease in the mass density of the halo, which would indicate both a truncation and a substantial flattening in the dark matter distribution.

The proposed project consists of proper motion measurements for the about 50 K giants that have been identified beyond 10 kpc from the plane of the Galaxy. For all, line of sight velocities are already available. The 50 stars have V $\leq$ 16; a tangential motion accurateto 5 km s^{-1} requires a proper motion accuracy of 40 μas. If the total space velocity is of order of 100 km s^{-1}, a distance accuracy of 5% is also required, which requires parallaxes accurate to 2 μas. Lower accuracy parallaxes (error of 10 μas) are required if trigonometric parallaxes are used to calibrate the distance scale for the nearest stars, which would then allow spectroscopic parallaxes to be used for the more distant stars.

4.6.5 Summary

1. Parallaxes and proper motions of 20–50 Perseus arm stars.
2. Parallaxes of 20 K giants
3. Parallaxes and proper motions of 50 B stars towards the anticenter
4. Proper motions of 50 halo K giants.

4.7 Astrometry of AGNs

Mitch Begelman, *Space Interferometry Science Working Group*

4.7.1 Internal Structure of AGNs

Broad Emission Line regions of quasars and Seyferts typically have angular scales of order 0.1-1 milliarcsec, and reprocess as much as 10% or more of the optical continuum into optical and UV lines. It is known that these lines are variable on timescales of a year or less (*i.e.*, at light-travel timescales), presumably in response to changes in the ionizing continuum. Neither the geometry of the emitting gas nor the isotropy of the ionizing radiation are known. If either of these is significantly asymmetric about the nucleus, then continuum variability might be accompanied by fluctuations of the apparent centroid of the optical emission. A ~1% effect might lead to fluctuations of order 3-10 μas. A good sample for this monitoring program would be the brightest Type 1 Seyferts (*e.g.*, NGC 5548, 4151, 7469, 3516, Mkn 335, and 1 Zw 1), which typically have $m_{\rm V} \sim 13.5 - 14.5$. (The optimal sample for a pilot project would include Seyferts and possibly bright QSOs with high amplitude optical variability.) Periodic astrometric measurements (every few months) should be correlated with optical light curves to look for systematics which might indicate a lopsided gas distribution or continuum anisotropy.

Bright knots in jets would be another interesting target. Here, the required dynamic range (unknown) might present a challenge. Optical knots are likely to be present on scales smaller than a parsec (corresponding to angular scales less than a milliarcsec) in sources which exhibit VLBI jets with superluminal motion. Excellent candidates would be the quasars 3C 273 and 3C 279, as well as other bright radio-loud quasars and BL Lac objects. If the knots can be resolved as point sources distinct from the nucleus, then detection of even mildly superluminal motion should be trivial within a few weeks (since it typically amounts to 0.1-1 $\mathrm{mas\,yr^{-1}}$). On the other hand, what can be done with AIM if the knot contains only a few percent of the brightness in the nucleus, and it cannot be distinguished as a separate source? (*E.g.,* suppose that the nucleus has $m_{\rm V} = 13$ and the knot has $m_{\rm V} = 18$). The AIM proposers should address their ability to deduce the presence of optical knots either directly, or through the secular drift in the centroid of the source position.

4.7.2 Proper Motions of AGNs

The nuclei of AGNs are sufficiently pointlike that their absolute proper motions may be measurable with high precision. At a redshift of 0.03 (1), a transverse velocity of 10^3 km s^{-1} corresponds to a proper motion of 3 (0.1) μas yr^{-1}. Thus, transverse velocities of nearby AGNs due, *e.g.*, to galaxy cluster potentials, should be detectable within a couple of years. Good candidates might be the nucleus of M87 in Virgo and NGC 1275 in the Perseus cluster. Bright type 1 Seyferts would also be suitable candidates (except that few of these are in rich clusters — they could be used to measure peculiar velocities outside of clusters). Only the nearest quasars would be suitable for this type of experiment. However, measurements of distant bright quasars distributed over the sky could be used to determine whether there are any systematic shears on very large scales. Even here, a program lasting 5-10 years with a precision of 3 microarcsec would be required to detect peculiar motions of $0.01c$ at $z = 1$.

4.7.3 Microlensing of Blazars

It has been suggested that some of the most dramatic examples of blazar variability could be due to microlensing of a distant AGNs by the stars in an intervening galaxy. It would be interesting to see whether the corresponding fluctuations in apparent source position could be detected. The typical angular fluctuation associated with a microlensing event caused by a star at distance D (at $z \ll 1$) is

$$\Delta\theta \sim 4.5 \left(\frac{M}{M_\odot}\right)^{1/2} \left(\frac{D}{100 \text{ Mpc}}\right)^{-1/2} \mu\text{arcsec}$$

(see, *e.g.*, Paczyński 1986, ApJ, 301, 503). The characteristic timescale for the event is given by the time required for the star to move transversely by a distance equal to the typical impact parameter,

$$\Delta t \sim 4 \left(\frac{M}{M_\odot}\right)^{1/2} \left(\frac{D}{100 \text{ Mpc}}\right)^{1/2} \left(\frac{v}{500 \text{ km/s}}\right)^{-1} \text{yr.}$$

Thus, motion during a microlensing event by an individual star might be detectable provided that the deflector is at sufficiently low redshift. Possible candidates would be bright BL Lac objects, which typically have measured redshifts of 0.03 to 0.3 and magnitudes in the range 13.5–14.5 (*e.g.*, OJ 287; Mkn 421, 180, and 501; PKS 0521-365 and 2155-304; 3C 66A and 371; and BL Lac itself). Note that if the microlensing interpretation is correct, it is not clear whether the measured redshift is that of the source or that of the deflector. PKS 0215+015 has exhibited a particularly dramatic example of variability, flaring from 18th to 12th magnitude, but it has a redshift of 1.8.

4.7.4 Summary

1. Detection of motion in the 6 closest type I Seyferts

2. Detection of motion in 3C273 & 3C279

3. Detection of secular motion in the nuclei of M87 and NGC1275

4. Detection of motion in 9 BL Lac objects due to microlensing

4.8 Rotational Parallaxes: Distances to Nearby Galaxies

Deane Peterson, *Space Interferometry Science Working Group*

4.8.1 Motivation

One of the critical issues of modern cosmology is the establishment of a reliable distance indicator independent of the redshift. This is accomplished by calibrating a series of standard candles, each useful over a certain range of distance moduli. Currently, the Tully-Fisher relation, relating the H I velocity width to absolute magnitude, is the final step in this process, although several other techniques are proving competitive (*i.e.* surface brightness fluctuations and planetary nebulae on shorter scales, SNe of both types on longer scales), and also require calibration.

The steps involved in calibrating these techniques are numerous and complicated; the distances are substantially removed from fundamental distance measurements such as parallaxes. As a result there is the probability of significant error in the final result.

4.8.2 Technique

With an instrument capable of measuring positions to, say, 5 μas and comparable proper motions per annum on objects approaching 20th magnitude, a technique becomes available to directly measure the distance to a number of nearby galaxies to high precision. In essence, this technique is similar to the "orbital parallax" technique used with binary stars, relying on Newton's laws rather than Euclidian geometry to obtain distances. (However, to distinguish the two I refer to this as a "rotational parallax").

To understand the approach, note that a transverse velocity of 100 km s^{-1} at a distance of 1 Mpc provides 21 μas yr^{-1} of proper motion. The main assumption involved is that the objects in question are basically in circular rotation (with an arbitrary rotation law, but for the purposes here it is useful that most have approximately constant velocity profiles outside the core regions). Assume the galaxy in question is inclined at an angle, i, that is comfortably between 0 and 90 degrees. Then, assuming a group of objects can be identified (see below) that take part in the circular motion of the galaxy, resolve the proper motions into components along the major axis, μ(M), and along the minor axis, μ(m).

First, consider an object exactly on the major axis. The circular velocity, $V_\circ$, provides a radial velocity, $V_r = V_\circ \sin i$, and a proper motion, $\mu(\mathrm{m}) = (V_\circ \cos i)/kd$ where k=4.738 if the velocities are in km s^{-1}, the distances (d) in Mpc, and the proper motions in μas. Secondly, consider an object on the minor axis (at the same physical distance from the galaxy's center). Here both the radial velocity and the minor axis component of the proper motion are zero, while the component parallel to the major axis is $\mu(\mathrm{M}) = V_\circ/kd$. Clearly, these three measures simultaneously solve for the (dynamical) inclination, the distance and the velocity, assuming purely circular motion. Observing a number of these objects over the face of the galaxy would also define the velocity law, where such is not already known (and should be done in any case for consistency) and would average out local deviations from circular motion due to spiral arms, warps, etc. Since the total velocity amplitude in giant spirals typically approaches 400 km s^{-1}, and assuming an inclination of 45 deg, the proper motion amplitude at 1 Mpc would be 60 μas yr^{-1}. Measurements would be accurate to a percent in principal, but limited to the extent there were significant deviations from circularity. Further, these numbers scale linearly with distance; the kinematics for this approach are available for remarkably distant objects, assuming sufficiently bright objects can be found. (Note these are relative proper motion measurements, and do not require an absolute positional grid).

In their "science paper" (Reasenberg *et al.* 1988, AJ, 96, 1731) the POINTS team and collaborators briefly discuss this technique in the context of the distance to M31, pointing out that a distance determination could be done to 1%. However, we note that these ideas are not original with this paper; the early efforts of van Maanen, so intimately involved in the Curtis - Shapely debates, were exactly to this point.

4.8.3 A – F Supergiants as Rotational Probes

Although there are perhaps several other classes of objects that can be used for this purpose, we identify the A - F supergiants as a suitable example. These objects are Pop I (*i.e.,* they partake in the circular rotation), are among the brightest (approaching -9.5 with many visible in any galaxy above -8) and have vanishing bolometric corrections (all the light comes out in the visual); they stand out well above the general background and have fewer problems with unresolved companions than, say, the Cepheids. Further, they are easy to find, either with simple two color photometry, or, when there are foreground problems, by their exceedingly large Balmer Discontinuities. Initial lists can be culled of remaining foreground objects by using the Oxygen I triplet at 7774 Å, which shows a large and well calibrated luminosity effect. These objects can be distinguished easily from the ground out to the distance of M81 (3.5 Mpc), to Virgo with some effort, and farther with HST.

4.8.4 The Observing Program

The only issue, then, is limiting magnitude. Using a cutoff of $M_V = -8$, these objects are 16.5 or brighter at M31 and M33, and 19.5 or brighter at M81. A large number of galaxies are included in this range. Besides the Local Group, there are spirals in the Sculptor group (NGC55, NGC247, NGC253, NGC300 and NGC7793, in the 1.5 Mpc range) and the M81 group (M81 and NGC2403, 3-4 Mpc), We have looked in the various compilations (Sandage & Bedke 1985, AJ, 90, 2001: "SB"; Tully 1988, Nearby Galaxies Catalog, (Cambridge: Cambridge Univ. Press); and Schmidt & Boller 1993, AN, 314, 371 (archived at NSSDCA-ADC): "NG") of nearby late type galaxies to estimate the various relevant quantities.

The results are listed in Table 8. Types and distances have been taken from SB unless indicated with an asterisk, where the recent Cepheid results of Freedman and her coworkers were substituted. In the case of NGC253 we have used Tully's distance. To estimate radial velocity amplitude we have used (half) the 21 cm width at the 20% level, W(20), as given in NG and/or Tully (shown averaged). Inclinations have also been taken from these latter two sources (shown averaged). The resulting major and minor axis proper motions were calculated separately from the two sources and averaged if both were available. We also show the apparent brightness of a unreddened star of $M_V = -8.5$, which we assume would be the typical stellar target.

Table 8: A Selection of Nearby Late Type Galaxies

NGC	Type	i	d	W(20)	μ(M)	μ(m)	V(M_v=-8.5)
		deg	Mpc	km s^{-1}	μas yr^{-1}	μas yr^{-1}	mag
55	Sc	84	2.0	196	1	10	18.0
224 =M31	Sb	77	0.77*	533	16	75	16.0
247	Sc	76	2.2	220	3	11	18.2
253	Sc	81	3.0	434	3	16	18.9
300	Sc	44	2.2*	163	8	11	18.2
598 =M33	Sc	56	0.84*	192	16	29	16.1
3031 =M81	Sb	57	3.6*	455	10	18	19.3
5457 =M101	Sc	24	5.2	192	9	9	20.0
7793	Sd	47	4.1	193	5	7	19.6

* Distance from Freedman and collaborators.

4.8.5 Observations Required

In order to assure some averaging over dynamical perturbations, and to improve overall statistics, assume 100 A – F supergiants are to be observed in each galaxy. This observing program will require observing 25 objects, say, on the major axis each on opposite sides of center, and another 25 each on opposite sides of the minor axis. Ignoring possible non-circular motions, we will want to determine the (double) amplitude of the proper motions on both axes to 1 μas yr^{-1} for this purpose. Equivalently, each of the 100 objects in a galaxy needs its proper motion determined to 5 μas yr^{-1}. (Assume accurate radial velocities are already available).

5 Synthesis Imaging With SIM: An Imaging Science Sampler

Ronald Allen, *Space Interferometry Science Working Group*

5.1 Introduction

The Space Interferometry Mission spacecraft is a design which is capable of high-precision crowded-field astrometry (Yu, Shaklan, & Shao 1993, Proc. SPIE Vol 1947 "Space Interferometry", page 209) using an extension of conventional synthesis imaging techniques familiar from radio astronomy *e.g.*, with the Very Large Array. With the current proposal for a 20-meter instrument, SIM has the capability to image in the optical at λ 500 nm with a resolution of $\sim$ 5 mas, over a small field of view (FOV) of $\sim$ 300 mas. The FOV can be enlarged in a straightforward way, at the expense of additional observing time, by using conventional radio-synthesis "mosaicing" techniques. While the majority of the observing time would be earmarked for positional measurements, this added capability would provide new science, both planned and serendipitous, and an important testbed for the development of future large dedicated imaging interferometer systems in space.

5.2 Science at the Resolution limit of the Hubble Space Telescope

In the post-Costar era we now enjoy, HST is capable of imaging with diffraction-limited resolution of $\sim$ 50 mas at λ 500 nm. However, only the Faint Object Camera (FOC) with its 14 mas pixels is capable of fully sampling this PSF (at roughly at least two pixels per PSF); the best WFPC2 can do is 46 mas in PC mode (unless the images are "dithered", at a cost of increased complexity and observing time). The Advanced Camera (AC) designs currently under consideration (Brown 1993, "The Future of Space Imaging", Space Telescope Science Institute) for a future HST servicing mission are explicitly intended to provide at least critical sampling, *e.g.*, with 24 mas pixels for the optical and near-UV. As an imager, SIM has the potential to provide an improvement by a factor of $\geq$ 8 over the best linear resolution HST can achieve with dithered WFPC2 or with the AC. SIM could also provide oversampled images which is preferable for the convergence of image restoration methods.

5.3 The Significance of a Factor of 8 Improvement in Resolution

In any field of observational astronomy, it is usually the case that the most exciting science is to be found at the limits of telescope sensitivity and angular resolution. Typically it is the factors of 2 that enable new science to be done. Numerous examples can be found from the comparison of the 4m telescope at Kitt Peak, with $1''.2$ resolution, to the 3.6m CFHT on Mauna Kea, with $0''.6$ resolution. For instance astronomers have attempted to detect Cepheids in Virgo galaxies at the 4m, but it took the CFHT to accomplish this feat (Pierce, Welch, McClure, van den Bergh, Racine, & Stetson 1994, Nature, 371, 385). There are other examples of outstanding science which has been enabled by a "mere" factor of 2 increase in angular resolution; we are anticipating *three* factors of 2 over HST with SIM.

With an increase of a factor 8 in resolution we may reasonably expect to discover entirely new and unexpected phenomena. As an example of this case we consider a comparison of the best ground-based images of the central regions of R136 in the LMC (about $0\farcs4$ resolution) to the higher-resolution images first obtained with speckle techniques on the ground, and later with HST+WFPC1 in space (without computer restoration, roughly $0\farcs1$ resolution). In this case the central "supermassive star" turned out to be a cluster of more normal stars, radically altering the explanation of the central bright source. Other examples of this kind can be found in the HST science program.

5.4 The Expected Sensitivity of SIM

In its imaging mode, the operation of SIM is analogous to the operation of Very Large Array. However, the noise properties of images are different, since the dominant source of noise is not the receiver but the signal itself. This problem has been considered by Prasad & Kulkarni (1989, JOSA A, 6, 1702), and the relation to the radio synthesis imaging case reviewed by Kulkarni, Prasad, & Nakajima (1991, JOSA A, 8, 499 and references given there).

In the case of SIM, the sensitivity in imaging mode at *e.g.*, $\lambda = 500\,\mathrm{nm}$ can be roughly characterized as follows: With the present design, 0.3 m apertures on a 20 m truss, a S/N = 5 is obtained in one resolution element (PSF = 5 mas) on a point object of mag = 26.5 in 20 hours of integration. While it is clearly time consuming to provide synthesis imaging at this level, the science can certainly justify some fraction of the time on orbit, and the experience gained will be invaluable in designing future imaging interferometers.

Equally relevant to imaging with SIM is the dynamic range, *i.e.*, the ratio of the faintest detectable emission to the brightest source in the field of view. The dynamic range of SIM is presently estimated to lie around 2000 presuming the phase instabilities to be random. This is unlikely to be completely the case, however. It is important to develop more realistic models of the phase stability of SIM and in particular its time dependance, and to evaluate the effects of realistic phase errors on realistic source models. Nevertheless, there is every reason to be optimistic about the performance of SIM in aperture synthesis mode.

5.5 Three Candidate Imaging Programs

From the rich set of imaging results now flowing from the refurbished HST one can identify many situations where an improvement in resolution would provide a significant scientific payoff even for relatively bright objects. We list here three examples as a "sampler" of the imaging science possible with SIM:

5.5.1 Symbiotic Systems

These are a heterogeneous group of variable stars with composite spectra, consisting typically of a hot and cool component in a binary system. The cool component is a red giant or an Asymptotic Giant Branch (AGB) star and the hot component is, most frequently, a white dwarf. In many symbiotic systems it has been suggested that much of the observed activity is the consequence of colliding winds (from the hot and cool components). Since typical separations of these systems are of the order of a few AU or more, the proposed instrument should be able to resolve the interaction region for nearby symbiotics. Good candidates may be V1016 Cyg, AG Peg, HM Sge, and R Aqr (*e.g.*, Murset et.al. 1991, A&A, 248,199; Paresce & Hack 1994, A&A 287, 154; Taylor 1988, in IAU Coloquium 103, 77).

5.5.2 Young Stellar Objects

The formation and evolution of Young Stellar Objects (YSOs) is characterized by the emanation of bipolar molecular outflows and highly-collimated optical jets. These outflows limit the amount of accreted material onto the protostar and its surrounding accretion disk. Similarly, the jets may play a role in the process by which forming stars lose their angular momentum. While it is widely believed that it is the energy from the accretion disk which powers the outflows and jets, it is not at all clear at present how the YSOs redirect the material which is infalling in the disk into highly collimated supersonic outflows (*e.g.*, Ray & Mundt, 1993, in "Astrophysical Jets", eds. Burgarella, Livio & O'Dea, 145).

Preliminary images with HST of the T Tauri star DG Tau were already able to determine that the jet is collimated at a projected distance of ~ 40 AU (250 mas) from the star (Kepner *et al.* 1993, ApJL, 415, L119). An increase in the resolution by a factor of 8 will enable us to resolve structures even closer to the inner parts of the disk, to measure the proper motions of knots in the jet and to determine the true collimation distance. These will allow us to place meaningful constraints on jet formation mechanisms. Similarly, observations of even younger objects (age $\sim 10^5$ yr) may allow us to observe the infall process onto the disk closer to the disk center (in objects like L1527 IRS, L1551 IRS5 ; *e.g.*, Kenyon *et al.* 1993, ApJ, 414, 773).

5.5.3 Black Hole Candidates in Virgo Cluster Galaxies: A Unique Opportunity

The combination of HST/WFPC2 images and HST/FOS spectra has allowed the successful detection of a 2×10^9 $M_\odot$ and 1.2×10^9 $M_\odot$ central black holes in the active galaxies M87 and NGC 4261 respectively (Ford, H.C., Harms, R.J., Tsvetanov, Z.I., Hartig, G.F., Dressel, L.L., Kriss, G.A., Bohlin R.C., Davidsen, A.F., Margon, B., Kochhar, A.K. 1994, ApJ 435, L27; Harms, R.J., Ford, H.C., Tsvetanov, Z.I., Hartig, G.F., Dressel, L.L., Kriss, G.A., Bohlin R.C., Davidsen, A.F., Margon, B., Kochhar, A.K. 1994, ApJ 435, L35; Ferrarese, L., Ford, H.C., Jaffe, W. 1996, submitted to ApJ). In both cases, optimum planning of the spectroscopic observations require previous high-resolution imaging of the regions containing the ionized gas in the nuclei of the host galaxies. At the distance of the Virgo cluster (≈ 15 Mpc), where M87 resides, the $0\farcs1$ resolution of the HST/PC is barely sufficient for this purpose. At the distance of NGC 4261, 30 Mpc, the task is beyond the limits of HST. Figure 4a is a WFPC2/PC image of the central 4 arcsec of NGC 4261, showing a dust disk surrounding a bright emission-line region. Figure 4b is a continuum-subtracted map of the Hα-emitting ionized gas. At the HST/PC resolution the emitting region (only a fraction of an arcsecond in size) is just barely resolved, but no morphological details can be seen.

From the results of Ferrarese et.al. we can model the Hα emission from NGC 4261 in Fig. 4b as a HST Planetary-Camera PSF-sized source of intensity 1.9×10^{-12}ergcm^{-2}sec^{-1}asec^{-2}

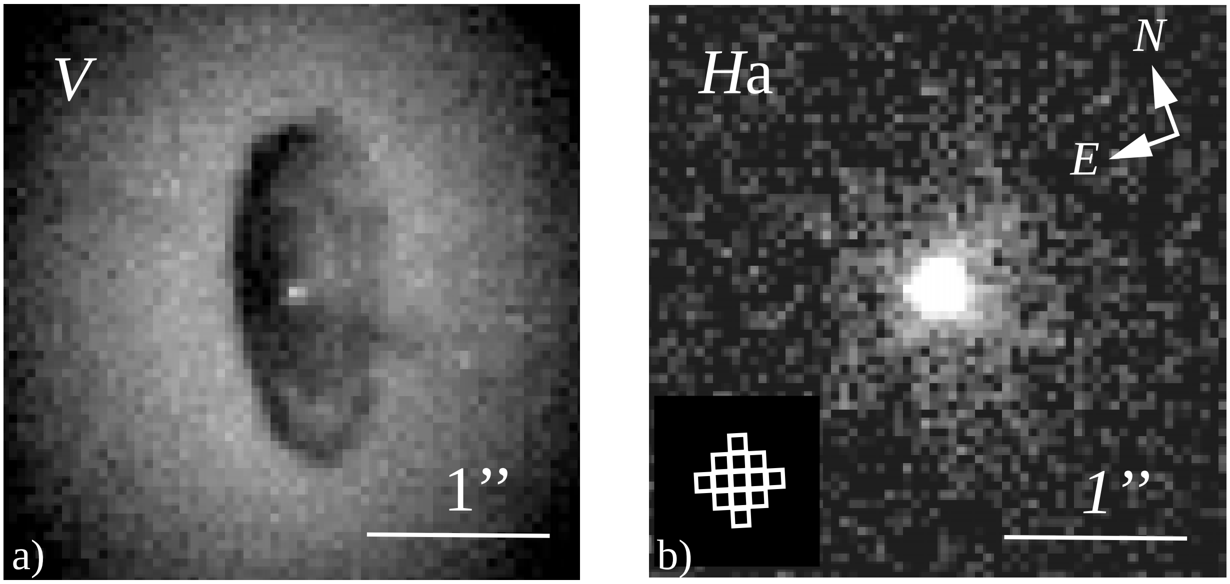

Figure 4: HST/WFPC2 V-band (a) and Hα (b) image of the dust disk in the center of the galaxy NGC 4261, 30 Mpc distant. At a resolution of $\approx 0\farcs1$ one sees details in the visual image of the disk, including a bright 'spiral like structure' wrapping around the South and North sides, and a 'dust jet' extending beyond the West and East edges of the disk. As viewed in Hα, the region in which the ionized gas is bound, about $0\farcs12$ FWHM, is undersampled by the PC, no morphological details can be seen, seriously limiting dynamical models (see text). The inset at the bottom left shows the pattern of HST Faint Object Spectrograph $0\farcs1$ apertures used to determine the kinematics of the ionized gas. The $0\farcs3$ field of view of SIM just covers the Hα disk; one can contemplate imaging with up to 60×60 pixels of $0\farcs005$ size. (Images courtesy of L. Ferrarese).

sitting on a disk of radius $0\farcs1$ and surface brightness $\approx 2 \times 10^{-12}$ergcm^{-2}sec^{-1}asec^{-2}. SIM could synthesize the Hα emission in this field to *ten times better resolution* ($0\farcs01$ pixels) in 24 hours of observing with S/N of 5 in each pixel over the source image which is approximately 18×18 pixels in this model. If instead we decided to spend the same amount of time as was spent with HST on the "Hubble Deep Field" ($\approx 558,000$ seconds), we could achieve a S/N of 13 per pixel. Such images would not only reveal details of the morphology of the ionized gas but, since SIM would operate in a dispersed fringe mode with the dispersion chosen to match the Hα signal width, *radial velocity* information would also be available with a velocity resolution of about 300 km s^{-1} at each pixel in the field. This would allow us to track the kinematics much further in towards the black hole and set even more accurate values on its mass. There is no other instrument currently planned which could produce such an image of black hole candidates in galaxies at and just beyond the Virgo Cluster.

6 Added Capabilities with SIM: Nulling

6.1 Introduction

Some of the greatest astrophysical benefits of all image-improvement technologies (including adaptive optics from the ground, space-based imaging, and optical/IR interferometry both from ground and space) is the ability to detect, image, or measure faint sources in the close proximity of much brighter sources; searching for planets or substellar companions of nearby stars is a prime example. In all cases, the technological challenge is to minimize the scattered light from the nearby source at small angular separation, since the dynamical range of intensities is usually limited by the detectors or instrument stability (see section 5 above). Hence, since the target (*e.g.*, a planet) signal is fixed, all one can do is to lower the background. One of the proposed extensions to the original OSI design, central fringe nulling (Bracewell 1978, Nature, 274, 780 and Shao 1991, Proc. SPIE 1494, 347) with one of the interferometers, offers the opportunity to achieve this at a higher level than otherwise possible, and thereby opens up another portion of the parameter space.

In the context of the planetary searches, nulling would mean that smaller or less reflecting planets can be detected closer in to the target star, perhaps approaching the terrestrial planets parameters in some cases. While this may ultimately prove to be the most important application of nulling, the technique will be invaluable in a variety of other astrophysical contexts. In the following paragraphs we describe some of the astrophysical situations in which a nulling capability may prove valuable.

For reference, in nulling mode a two element interferometer provides a θ^2 response near the central null (θ is the angular distance off axis times the usual interferometer resolution gain factor, baseline over λ). A 20 meter baseline 2-element nulling interferometer operating at $0.7\,\mu$ would then provide 5 magnitudes of suppression or more up to 0.7 mas off axis, 10 magnitudes over 70 μas and 15 magnitudes (ie, 10^6) over $7\,\mu$as. In turn, the Sun at 10 pc would subtend 1 mas (angular diameter, *i.e.*it would be suppressed by almost 6 magnitudes), a 13th magnitude K star in the Taurus cloud (150 pc) would subtend about 50 μas, and a 1 pc broad line emitting region around an AGN at 20 Mpc would subtend 10 mas.

6.1.1 Binary Systems

Many binary star systems present a similar situation to planetary systems, in that one component is much brighter than the other. Since binary stars are the primary route to the determination of physical parameters of stars, in particular the masses, an ability to see the fainter component in addition to the brighter object will be invaluable. Examples of binary systems in which one component is much fainter than the other include systems containing black holes and neutron stars, and systems with widely disparate masses. The binary separations are in many cases similar to those expected from planetary systems, so the same technology should yield equivalent improvements in understanding these objects.

6.1.2 Stellar Winds

Stellar winds and outflows provide another situation in which a nulling capability would be important. Such outflows are crucial in many areas of astrophysics, from massive main sequence stars to planetary nebulae to supernova explosions. To take but one example, a nulling capability would have allowed the ring around SN 1987a to be identified and studies long before it reached a size observable from HST. In this case, as in most wind phenomena, the interesting physics occurs near the base of the outflow, where light from the central object ordinarily prevents detailed observations.

6.1.3 Active Galactic Nucleii

Another exciting possibility is to be able to map the structure of central regions of the nearby active galactic nuclei, especially Seyfert 1's, and perhaps even the nearest quasars. The broad-line regions of AGN are estimated to be a parsec or less in size, and thus would have 10 mas apparent diameters in the nearest AGN. This would allow the possibility of a direct measurement of their sizes which would provide important input for the models of AGN. The narrow-line regions are expected to have physical sizes of 100 pc or more, and thus can be well resolved and mapped in the nearest AGN, or perhaps even out to the Virgo cluster, using this technique.

One could also hope to detect small-scale optical jets in AGN (optical counerparts) of the radio jets seen in VLBI maps, and detect their proper motions. Direct comparisons of optical measurements and the corresponding VLBI radio data could then be used to constrain the physics (radiation mechanisms, magnetic fields, etc.) of these jets and the circumnuclear regions through which they penetrate. Recently, jets have been observed emanating from accreting stellar mass black holes in our own galaxy. The use of nulling interferometry on these sources would provide access to detailed images of the base of a relativistic jet.

6.1.4 Gravitational Lenses

One additional application is to measure the fine structure of bright, gravitationally lensed quasar images. These images are really caustics of the gravitational optics, and their structure can provide additional constraints on the geometrical models for a specific lens. For the lenses where the additional necessary information exists (*e.g.*, time delays and the redshifts) so that measurements of the Hubble constant can be attempted, this could provide an improved accuracy.

No other methodology, save for space-based interferometry with baselines an order of magnitude larger, could provide comparable observations of these important astrophysical phenomena.

7 The European Astrometric Satellite, GAIA, and SIM

GAIA (Global Astrometric Interferometer for Astrophysics) is an orbiting astrometric interferometry mission that is currently under consideration by ESA in the framework of the Horizon 2000+ plan. The technical characteristics of the most current GAIA design, as described by Lindegren and Perryman (1996 A&A, in press; also 1995, Future Possibilities for Astrometry in Space: A Joint RGO-ESA Workshop, eds. Perryman and van Leewuen, ESA AP379), include: limiting magnitude V $\sim$ 16; number of target $\sim 5 \cdot 10^7$ (complete to V $\sim$ 15; and astrometric accuracy $\sim 10\ \mu$as at V $\sim$ 15 over a 5-yr mission lifetime, for positions, parallaxes, and yearly proper motions. This is to be achieved by three coplanar imaging (Fizeau) interferometers, each with a baseline of ~ 2.5 m, scanning the sky as the spacecraft spins with a period of a few hours. This design is far from final, and even very basic design choices, such as the number of interferometers and the detection strategy, are still being discussed. An extensive discussion of various options for GAIA can be found in Perryman and van Leeuwen (1995).

The main science driver of GAIA is a thorough survey of the overall structure of the Galaxy, including both its geometry and its kinematics. In this sense, the proposed GAIA mission has a very clearly defined scientific target, which strongly drives and constrains its design characteristics.

GAIA is in a much less mature state than SIM. Its feasibility will depend on major technology advances in two areas, detector characteristics and metrology. The challenge for detectors will be to be able to image an area of about one square degree with a resolution of $0\farcs02 \times 0\farcs2$; this may be addressed using modulating grids or newly designed CCDs (as currently conceptualized the grid size is $27'' \times 13\farcs5$, creating the potential for confusion in crowded fields). The metrology challenge is to track the relative motions of separate optical components in the different interferometers over time scales between 1 and 10^4 s. Future ESA support for GAIA will be based on whether the stated goals ($10\,\mu$as accuracy at V = 15) appear feasible after the design has consolidated.

SIM and GAIA are largely complementary missions. SIM has been designed and optimized for pointed observations; the longer baseline, the ability to point at a single source for an extended period of time, and the real-time monitoring of the position of the baseline allow higher accuracy on targets so faint (V $\sim$ 20) that they cannot even be detected by GAIA. This greatly limits the extragalactic science that can be addressed with GAIA. GAIA will not be able to increase the measurement accuracy for a specific target by observing it for a longer time: the duration of each observation is fixed "a priori" by the spin of the spacecraft. Note that the required measurement accuracy quoted for GAIA is "per mission", and it will only be achieved by combining the full five years' worth of observations; SIM can reach similar accuracies in a single observation. In addition, GAIA will also be on a fixed schedule of observations: each target will be observed at pre-determined epochs, which will depend solely on its position in the sky. This will be a substantial limitation for observations of binaries. As a survey mission, GAIA makes up for its limitations in single-target observations by virtue of the number of targets; GAIA's ability to determine positions and velocities for a very large number of stars within the Galaxy will make it extremely valuable for broad galactic structure problems.

GAIA and SIM can greatly enhance each other capabilities and the scientific progress in the field of astrometry. GAIA will be able to provide a large-angle network of reference stars to provide a uniform reference system that may be useful to SIM, particularly if there is a significant time interval between the two experiments; at the same time, SIM can make key observations that can fix this network relative to others, such as a network of QSOs that are generally too faint for GAIA to observe with the needed accuracy. In addition to the fainter limiting magnitude and higher accuracy, SIM has several capabilities that GAIA lacks in the current or any foreseeable incarnation; among these, the ability to study complex sources (either multiple point sources or point+extended systems) via the imaging capability; the ability to study time-critical targets (variable, targets of opportunity, binaries, etc); and the ability to serve as a potential test bed for new technology developments, such as the nulling capability. If GAIA were available in a similar time frame as SIM, it would lift part of the burden as a general-purpose survey instrument, and leave the latter more able to concentrate on its unique abilities.

The relationship between SIM and GAIA can perhaps better be illustrated in reference to the sample science program provided by Section 4. About half of this program is beyond the capabilities – and indeed, the design choices – of GAIA; namely, all the binary and active star part, the Local Group section, and the extragalactic section. The globular cluster program may or may not be within GAIA's capabilities, depending on how these will be determined ultimately. The Galactic Structure part, on the other hand, would be carried out by GAIA in much more detail than is conceivable with SIM, and many new projects are in fact listed in Lindegren and Perryman (1996) in this area. Thus, the overlap between GAIA and SIM is much less than their complementarity.

8 Technology Issues and the Technology Plan

The SISWG Technical Panel was asked to assess the issues pertaining to the technology readiness of an AIM/OSI implementation as well as the value of AIM/OSI as a technological precursor to future space missions. We describe here the outcome of the Technical Panel deliberations in response to the following three part charge from the overall working group:

1. Certify that the OSI design concept for the AIM Mission is capable of meeting the AIM measurement objectives. As a critical part of the certification, produce a set of curves representing OSI performance as a function of astrometric accuracy vs stellar magnitude vs integration time.

2. Review and evaluate the Technology Plan for Space Interferometry Missions. This is intended to provide technology development crucial to the success of OSI and other space-based interferometry missions, with regard to comprehensiveness, priorities, and implementation approach.

3. Consider several potential modifications to the OSI concept, and evaluate both the impact of these modifications and whether such modifications would make the OSI mission a better stepping-stone to future missions. Modifications for consideration: (a) increase the baseline to 20 meters, (b) operate into the thermal IR, (c) increase mission lifetime to 10 years, (d) incorporate starlight nulling optics, (e) operate further into the UV, and (f) simplify the design in order to reduce cost.

Conclusions regarding these three areas are summarized, in turn, below. The reader is referred to the report of the Technical Panel's meeting of 15-16 August 1995, Appendix A of the OSI Certification Report, for a full accounting of the rationale behind the conclusions.

8.1 OSI Certification

The Technical Panel found that the OSI design concept is capable of accomplishing the AIM science mission. Given the anticipated error sources, an astrometric accuracy of 5 - 10 microarcseconds would be expected for 17th magnitude stars and one hour integration times. The analysis supporting this conclusion is presented parametrically in Figure 5 where OSI's astrometric accuracy is plotted as a function of star (visual) magnitude and integration time.

The Panel noted that the current OSI weight margin of more than 1000 kg is crucial to the feasibility of OSI. With the design's early state of development, the weight margin provides a cushion to overcome difficulties as the design matures. Specifically, the weight margin can be used to reduce cost or to overcome technical problems. The expected growth allowances ("contingency") make the weight margin realistic. This is a proven methodology, which has been shown throughout the spacecraft development community to be an effective way to predict final spacecraft weight. Design or mission changes which greatly reduce the weight margin would adversely affect feasibility.

The complexity of OSI, especially the high mechanism count, is an area of concern. Although mitigated somewhat by the fact that the system is currently single fault tolerant and

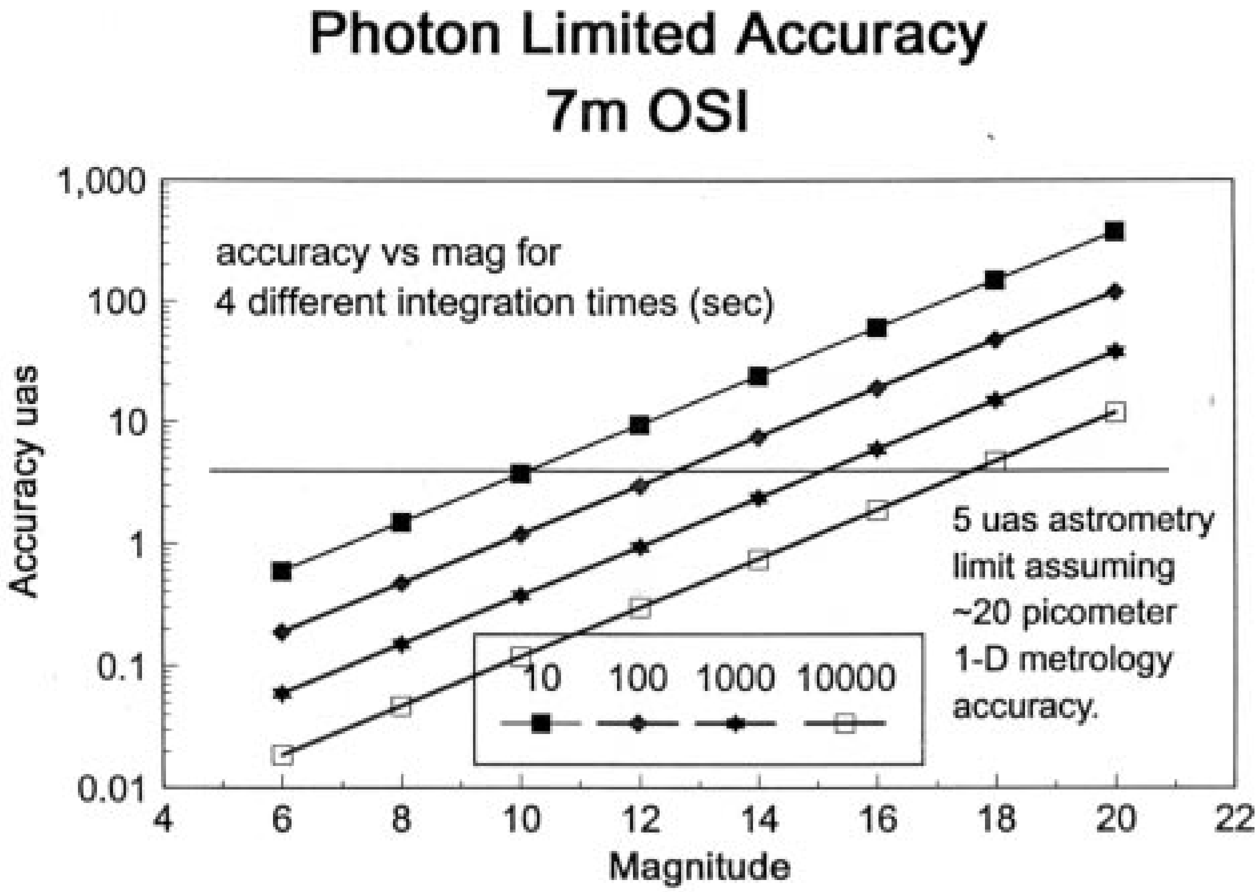

Figure 5: Photon limited positional accuracies for 4 different integration times. Also indicated is the point where meterology accuracies of 20 pm over a 7 m baseline would begin to dominate.

has considerable mass margin, which would allow the introduction of additional redundancy, the Panel recommended that reliability issues should be pursued vigorously in the next phase of system design.

The OSI spacecraft design is in a relatively immature state. There has not been a sufficient commitment of resources to perform a design iteration which would be comparable, for instance, to the level of detail consistent with a competitive industrial proposal effort for a program of this scope. Serious consideration should be given to accelerating the design effort in the near term. A bottom up cost estimate should be included in this effort.

8.2 The Technology Plan

The Technical Panel was unanimous in its belief that the ability to implement OSI in a cost effective manner and at acceptable risk is dependent on the initiation of an aggressive and well coordinated technology development program. The technology development program should be regarded as an organic element of the OSI effort. The toughest technical challenges for OSI are in the areas of precision stabilized optics and metrology. Implementation of the Technology Plan for Space Interferometry Missions (an addendum to Appendix A of the OSI Certification Report) is critically important to reduce these risks.

In general, the fundamental structure of the Technology Plan is solid and well developed. The following points summarize the sense of the Technical Panel with regard to areas of emphasis or concern:

1. The ground testbeds (MPI-2 and the Microarcsecond Metrology Testbed) are very important. Integration of this precision technology will probably surface the most obscure technical issues for OSI, enabling the development of solutions without program impact.

2. The Technology Plan does not call for the development of advanced lightweight optics or structures technology. Neither is autonomy technology for on-orbit alignment, calibration, target acquisition, and fault detection identified as of high priority. Consideration should be given to adding these technologies to the plan.

3. Work is needed on the Technology Plan to be more specific in the Integrated Modeling (IMOS) area. The major near-term goal for IMOS is to be useful as a spacecraft development tool, giving designers information early in the design cycle about the effects of thermal and structural impacts on performance. However, long-term plans for IMOS development were less clear and should be fleshed out.

4. Some of the components defined for work in the Technology Plan may not represent true technology issues. In some cases, these may simply be components which are required for development of the testbeds. If existing technology will suffice, the most cost-effective procurement of adequate hardware should be purused.

5. Every effort should be made to involve the larger community in the implementation of the Technology Plan. This is particularly important when it comes to industrial firms since, without their involvement, insight gained by JPL during the execution of the technology program will not benefit those companies that have a leading role in developing the OSI flight system.

8.3 Potential Modifications to the OSI Baseline Design

Modifications to the 7-m OSI baseline were considered both from the perspective of a precursor function for an ExNPS infrared interferometer and/or a next generation space telescope as well as from the perspective of cost impact to the OSI mission. Table 9 summarizes the conclusions reached. The first column reports the Panel's attempt to quantify the benefit on a scale of zero to ten, with primarily ExNPS in mind. Note that OSI, without modification, constitutes a reasonable precursor to ExNPS, given all the metrology, pointing and path-length control, and vibration isolation/suppression technology that will be demonstrated. The second column represents a first cut at attempting to assess the cost of each of the

OSI AS PRECURSOR

	Benefit to ExNPS & HST / Beyond	Cost Impact to OSI
NO OSI	0	0
CURRENT OSI (7-meter)	5	1.00X
CURRENT OSI w/ NULLING	5.75	1.05X
20-METER BASELINE OSI		
Deployment not traceable to ExNPS	5.75	1.25X
Deployment traceable to ExNPS	8	1.40X
COLD OSI (7-m, 70K - 100K)	6.5	1.8X
COLD 20-METER BASELINE OSI w/ NULLING	10	2.25X

Table 9: Cost multipliers and technology demonstration contributions for various suggested extensions to the original 7 m OSI design.

listed modifications. Cost is computed as a multiple of the cost of the current OSI, which is given the value "X".

Other points to be made with reference to Table 9:

1. Extension of the OSI interferometric baseline to 20 meters would demonstrate a significant amount of the technology required for ExNPS. In particular, the baseline would be from 20% to 40% of the ExNPS baseline currently being proposed. If a deployment technique is used which is traceable to ExNPS, then the essence of that deployment method could be demonstrated in OSI.

2. Extension of the OSI baseline to 20 meters would significantly increase the complexity of OSI, and would add risk to the deployment. The deployment would still, however, be well within the range of deployments which have been accomplished, in terms of both size and complexity.

3. Maintenance of the OSI system at a cold temperature, representative of ExNPS, would

have a major impact to OSI, and would probably make the program prohibitively expensive.

A majority of the technology panel felt that extending the OSI baseline to 20 meters should receive serious consideration in the near term, not only for its value as a technological stepping-stone to ExNPS but also due to the enhanced astrometric and imaging science that could be accomplished. However, a strongly argued minority opinion held that instead of trying to make OSI more capable (and consequently more complex and expensive), NASA should instead be trying to simplify OSI to the greatest extent possible and thereby keep it within a reasonable cost cap.

9 Conclusions

The advent of technologies and technical capabilities that enable an experiment like SIM came on Astronomy without much warning. The realization that the potential existed for a gigantic leap in positional measurement precision became clear during the construction of the Bahcall report, and was immediately seized on as filling a longstanding, critical need.

As outlined in this report, the potential is real. The potential for major scientific advances along a broad front has been described in detail. Almost no area of astronomical endeavor is missed. Starting with solar system motions and dynamical reference frames, going through a myriad of stellar and galactic structure issues, and on through the extragalactic arena and the major issue of distance scales, the impact of this experiment will be immediately felt.

Further the potential that the instrument will actually work as proposed is real. Described here in summary is the careful review given the design and associated technology developments by the Technology panel. Tremendous progress has been made on critical capabilities and the path to be taken in demonstrating the remaining technologies is laid out in the Technology Plan. What remains to accomplish on the technology end requires providing early and substantial funding for the remaining critical technical demonstrations, as described.

At the same time, it is becoming clear that interferometry, applied to specific and carefully drawn questions, will become a space technique used more and more commonly in the future. Clearly, there is a limit to the size of monolithic mirrors that can be launched. Whether future imagers constructed of smaller elements are mostly filled or vastly dilute, the techniques learned in this first generation of interferometers will be critical.

As the first step in space interferometry, SIM is central. Its scientific return amply justifies its cost. As a proving ground for technical capabilities required for the next generation interferometers it seems the logical choice. The conceptualization of the experiment is mature. What is needed now is agressive funding of the critical technology developments and demonstrations that are next in line in the Technology Plan. All this is within our grasp and within our capabilities. It is a scientific opportunity that cannot be missed and a technology challenge that cannot be skipped.

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